RESEARCH AND DEVELOPMENT OF AN APPROPRIATE ELECTRIC POWERED WHEELCHAIR FOR INDIA

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The need for assistive technology (AT) extends far outside of the countries where users have the financial capacity to buy them, or there is a social welfare infrastructure to subsidize their purchase. In developing countries, where both technology and financial resources are scarce, AT users face tremendous challenges to find high-quality devices that are affordable. This scenario is in part due to organizations who transfer sub-standard AT to these countries by taking a 'something is better than nothing approach' to a clinically and technologically challenging problem.

The goal of this work is to develop and demonstrate AT design and technology transfer strategies that take into consideration the clinical and technological needs of the intended user population. Although other projects have and do take these important user-centered factors into consideration, this work represents the first comprehensive attempt from an academic perspective, where hypotheses are proposed and tested, and design goals are described and evaluated with respect to the final product. The main focus of this work is on mobility devices (wheelchairs, specifically) although many of the protocols and techniques could be extended to address AT design and technology transfer to developing countries in general.

The first part of this dissertation (Chapters 1 & 2) focuses on the background literature, and proposes a model describing the important factors influencing the success or failure of a wheelchair technology transfer project. The second part of this dissertation provides a case study in the development of an electric powered wheelchair for users in India. First, an analysis of a commercially available low-cost powered wheelchairs were evaluated (Chapter 3). Second, a study to assess the needs of users in India was performed using a modified ethnographic approach (Chapter 4). Third, the design and evaluation of a novel low-cost electric powered wheelchair for Indian users is described (Chapter 5). The final chapter (Chapter 6) discusses the implication of this work and suggests future directions. The entire drawing-set for the second generation prototype developed here is also included, allowing others to build upon the approach and the design developed here.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

I owe special acknowledgement to all of the guidance support I have been given to help me complete this research and degree. First, without the support, guidance and latitude Dr. Cooper provided, this work would not have been possible. Apart from his design help, his insight and expertise on rehabilitation science in developed countries has provided a valuable model for what is possible in developing countries. The rest of my committee has also provided critical support for this work. I am grateful to Dr. HS Chhabra for providing support and guidance during my trips to India, Dr. Seelman for her friendship and help in defining my dissertation work and career path, and Dr. Ding for her support and guidance at HERL.

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My friend and family will be surprised that I am finally out of school—they were all supportive throughout the process, but probably had doubts it would end. My mother and father have always encouraged and supported me through school and my random bouts of traveling. My stepfather, Mike, taught me how to design and build devices, and sent me on this academic and career path. My sister, Kirk, Ivar, and Megan have all been a huge source of support. I want to dedicate this to my grandmother, who has always been an important force in my life, and who I will never stop missing.

1.0 INTRODUCTION

1.1 MOBILITY TECHNOLOGY FOR PEOPLE WITH DISABILITY IN DEVELOPING COUNTRIES

Individuals with disabilities in developing countries face extraordinary hurdles to participate fully in society. Not only are they typically the lowest wage-earners [1], but assistive technologies (ATs) are scarcely available, and what is available is often low-quality, does not meet the users' needs, and is not appropriate in the users' physical and cultural environment [2, 3].

The number of people with disabilities worldwide is unknown, but the World Health Organization (WHO) estimates approximately 10% of any population are people with disabilities (PWD) [4, 5]. The number of potential wheelchair users worldwide is also unknown, and estimates vary widely, from 20 – 100 million ([6, 7] with only approximately 1% who currently have them [8]. As a rough estimate, the WHO suggests that approximately 1% of any population could benefit from the use of a wheelchair. This number holds true in India, where the population is approximately one billion, and there are an estimated 10.6 million individual with locomotor disabilities [9].

This tremendous demand for wheelchairs and other mobility technology is met typically with low-quality devices, which are based on antiquated designs. There is ample anecdotal evidence that these devices fail quickly in the rough terrain of developing countries but scientific evidence of these failures are scarce, primarily because transferring AT has historically performed by charitable organizations who have not published records of the outcome of these devices. One recent scientific follow-up study of 162 depot-style manual wheelchair (MWC) users in India [10] revealed that over 70% of users' wheelchairs had been abandoned or sold, and only 7.4% were used regularly. Non-use was attributed to problems maneuvering in the environment (33.9%); pain, fatigue, discomfort (28.6%); and device failures (15.2%). Another follow-up study of 60 wheelchair recipients from two district rehabilitation centers in India [11] found that a minority of users self-propelled (~10%) and most were attendant propelled (~50%). Wheelchairs were predominantly used outside the home because of accessibility issues, and many of the users complained of problems with casters and fears related to the stability of the wheelchairs (60%). The results from these studies are not surprising considering the wheelchairs provided to these users were of low quality and designed for institutional use. Research has shown that these wheelchairs are inappropriate for most individuals in well-built environments in the industrialized countries because of their poor maneuverability and durability [12-14]. Some authors have suggested that low-quality devices can be more hindrance then help [15-20] in developing countries. Unfortunately, in developing countries anecdotal accounts are the primary source of this information.

The majority of this evidence is related to wheelchairs because they are commonly transferred devices. One author wrote that the hospital-style wheelchairs transferred to South Africa were "useless" [15], and that accurately sized and designed wheelchairs were crucial [2], especially to avoid secondary injuries [19], such as commonly deadly pressure ulcers. A recent follow-up study of 447 spinal cord injury patients in India highlights the need for pressure ulcer prevention [21]: 182 patients had pressure ulcers (33%); furthermore, 58 individuals out of the total cohort (787) had died (7.4%), where 22% of these deaths were attributed to septicemia secondary to pressure ulcers.

Interestingly, the problem of poor quality wheelchairs in developing countries is not a technical one. There are several proven wheelchair designs [3, 22] which are only slightly more costly than a hospital-type design, and who's designs are provided free of charge. The source of the problem appears to be that manufacturers, vendors, healthcare providers, and governments are uneducated about the features and quality of wheelchairs that should be manufactured and distributed. This is in part due to the users' inability to demand devices that will best suit their needs. In typical market situations, consumers demand the features and the quality of products with their purchasing power. In most countries, wheelchair users typically do not purchase their wheelchairs; in developed countries, insurance companies cover the expense, and in developing countries the costs are borne by charitable foundations or government subsidies (e.g. [23]). Because of these third-party payers, the quality and features are usually controlled by the distributors or through policies that specify the types of devices that are permitted. In developed countries, these policies are the main source of protection for the user, requiring that devices meet certain standards, [24, 25] and that clinical services be provided which each device. In developing countries, these policies do not exist, are not enforced, or are not stringent enough to protect the users from poor quality devices. For example, In India and China, the national standards for wheelchair technical quality are significantly less stringent than those published by the International Standards Organization (ISO) [26] even though the terrain in the rural environments of these countries are rugged and unforgiving on wheelchairs [10, 11]. In India, these low standards have enabled the largest AT manufacturer in South-Asia—an Indian government owned entity—to continue to distribute sub-standard wheelchairs at a pace of 45,000 per year [27].

Recent progress on international guidelines and policies should slow the trend of low-quality manual wheelchairs (MWCs) distribution in developing countries. In 2007, the International Society for Prosthetics and Orthotics (ISPO) plans to publish guidelines on Wheelchair Provision for Less Resourced Environments [28]. These guidelines have been written by a host of experts in the field with support from ISPO, the World Health Organization (WHO), and the US Agency for International Development (USAID). Topics include Policy Issues, Services, Design and Production, Training, Roles of Stakeholders, and Evidence of Good Practices. It is hoped that WHO member states will adopt and follow the guidelines, which suggest that wheelchairs be tested to ISO standards. Policy and service delivery methods will also ensure that the MWC user is protected and properly fitted and trained to use and maintain the device.

On a broader scope, the UN Convention on the Rights of People With Disabilities was passed by the general assembly on December 6^{th}, 2006 [5]. The convention provides details of the rights of PWD, and sets methods on how to implement and ensure those rights in member states. Of particular interest related to mobility devices is Article 20 (Personal Mobility):

States Parties shall take effective measures to ensure personal mobility with the greatest possible independence for persons with disabilities, including by:

a. Facilitating the personal mobility of persons with disabilities in the manner and at the time of their choice, and at affordable cost;
b. Facilitating access by persons with disabilities to quality mobility aids, devices, assistive technologies and forms of live assistance and intermediaries, including by making them available at affordable cost;

c. Providing training in mobility skills to persons with disabilities and to specialist staff working with persons with disabilities;
d. Encouraging entities that produce mobility aids, devices and assistive technologies to take into account all aspects of mobility for persons with disabilities.

On the opening day for signing the treaty, 81 member states along with the European community signed, and one country ratified it. Given the rapid adoption, it will likely become international law quickly, and finally help ensure the equality that PWD deserve.

For most member states, implementation of the convention will require significant efforts to enforce the new policies and legislation, as well as large investments in healthcare infrastructure and training programs. Even to meet the requirements of Article 20 will be an enormous undertaking for developing counties where high-quality mobility aids are typically imported and are prohibitively expensive. It is likely that the introduction of some of the affordable mobility aids will begin with AT technology transferred from developed countries, where the designs meet international standards.

Unfortunately, there are only a few successful examples of AT technology transfer to developing countries to use as a guide. For the most part, when large-scale AT technology transfer has been attempted, they have failed because the devices are not appropriate for the environment in developing countries. The few AT tech-transfer examples which have been successful are on a relatively small scale, and it is unclear whether they would be scalable or economically feasible to meet the requirements indicated by the UN.

1.2 PERSONAL MOBILITY TECHNOLOGY: PAST AND CURRENT TECHNOLOGY TRANSFER APPROACHES

The quintessential example of the failure in AT transfer, and the transformation of the device into a widely successful product is the Jaipur Foot prosthesis. Dr. P.K. Sethi, a surgeon in India, found that Western-designed Solid Ankle Cushioned Heels (SACH) transferred to India in the 1960s did not meet Indian users' needs: the stiff foot of the prostheses would not allow squatting, and the aesthetics of the foot made it embarrassing for the people to use while walking barefoot; both common practices in India [29]. Dr. Sethi addressed this failure by developing a more pliable foot with anatomical aesthetics. At a fraction of the cost of the SACH foot, the Jaipur Foot is a lightweight, culturally- and environmentally-appropriate device. The Jaipur foot is an example of a user-centered device, which has been mimicked to some degree by individuals transferring wheelchairs to low-income countries.

Whirlwind Wheelchair (www.whirlwindwheelchair.org) founder and design engineer Ralf Hotchkiss has used a *user-centered* and *open-source* approach to designing wheelchairs and starting small, grassroots workshops in low-income countries [19, 20, 30]. Design improvements come from these shops around the world, which has made the Whirlwind Wheelchair a low-cost, durable, highly maneuverable MWC that is appropriate in developing regions.

Motivation Charitable Trust (www.motivation.org.uk), a UK based not-for-profit organization specializes in training seminars for local wheelchair manufacturing and service delivery training in low-income countries. Apart from their small-scale, local manufacturing model, they also designed and coordinate the transfer of imported wheelchair from China.

Our laboratories, similarly, used focus groups and information regarding the terrain in India, and developed a user-centered design for adult manual and pediatric wheelchair for a large-scale wheelchair manufacturer in India (Chapter 2). While systematic design processes were likely performed in all of these cases, very little literature has discussed the pitfalls of the projects. We have published information regarding our design process and critical factors in AT technology transfer [3].

One thorough discussion of the design process for AT for low-income countries was written by Mulholland et al. [31-33] who performed focus groups and interviews to elicit feedback about a prototype manual mobility device for women with mobility impairments in India. Mulholland's manuscript is valuable, in part, because it documents the type of mobility technology that would help women overcome these challenges. Mulholland, in her manuscript, also documents the process of gathering feedback in Indian and its challenges. As the first and only paper thoroughly describing this process, it establishes a foundation from which other researchers can build to ultimately optimize the process of AT transfer to low-income countries. What Mulholland found, and what is evident from the above examples, is that the intersection of rough-terrain, cultural and social norms, and low-income make designing mobility devices for low-income regions non-obvious. A designer must not assume that a western-style device will be appropriate for the cultural, physical, or technical constraints present in these regions. Rather, a device needs to be specifically designed (or modified) for these regions to ensure it is viable. The value in Mulholland's approach is that she systematically investigated the viability of her mobility device with users and their family members (the primary stakeholders). Another important aspect to investigate is whether the device can be manufactured in the target region, and/or whether or not it is safe from a clinician's perspective, which requires more stakeholder feedback.

For effective AT technology transfer, all barriers to use, delivery, and production must be evaluated and ameliorated. These approaches are commonplace in higher-income countries, where market competition requires thorough design, market, and production reviews to be performed. If the cost to benefit ratio is prohibitive because liabilities are too high (because the device is unsafe), the market share is too low (because the device is not widely applicable), or the production costs are too high, the device will not be manufactured. The same critical evaluations should be performed when designing or transferring a device to low-income countries.

The consequences of overlooking these important factors when transferring MWCs to low-income countries can be substantial. Scientific evidence suggests over 70% of the depot-style wheelchairs go unused or require an assistant [10, 11], and published anecdotal evidence and personal experience from the author provides overwhelming evidence of the failures of these projects. Cleary, the primary effects of these device failures are that the MWC users are left without an operational device, or worse, they suffer from potentially deadly pressure ulcers [21]. But these failures also affect the organizations sponsoring and carrying out these projects—if there is no clear accounting of the outcomes of these projects, or it is evident they are failing to meet their goal, then future projects are unlikely to be funded and ongoing projects may lose funding. It is a vicious cycle that ultimately hurts the wheelchair users these projects aim to empower.

AT technology transfer efforts are on the rise with the industrialization of populous countries (such as India and China), and the likelihood that the UN Convention of the Rights of

PWD will be ratified. If these future efforts follow the same path as the past efforts with the SACH foot and the MWC, they will quickly fail the user and have to undergo a time-consuming and costly re-design cycle. Avoiding these inefficiencies is critical to meet the needs of PWD in developing countries.

1.3 NEED FOR PRODUCT DESIGN PROTOCOLS AND TECH-TRANSFER METHODS

To improve the efficiency of AT technology transfer, and minimize the risk of repeating these past mistakes with other AT, the factors, or variables, which influence the success or failure of these projects, need to be investigated. Considering these variables during the initial stages of the device design and/or device transfer will increase the chances that the device will be successful. Monitoring these variables (e.g., device quality, outcomes, etc.) while the project is underway will provide important information on how to adapt the project to unexpected changes (such as materials, worker training, overhead, consumer profiles, etc.). This is an especially important time to understand these variables, since as the economies grow of the most populous and low-income countries, such as India and China, their health infrastructures will improve, and the purchasing power of their citizens' will increase. In parallel with the ratification of the UN Convention on the Rights of People With disability, this purchasing power will create a demand for more sophisticated, but still low-cost AT.

While successful, the AT technology transfer approaches by Whirlwind Wheelchairs International, Motivation Charitable Trust, and Mulholland's group have been performed among an isolated group of MWC users and product designers. It is unclear whether duplicating these approaches for larger-scale technology transfer would be feasible or cost effective. An important goal should be to develop AT technology transfer methods that utilize the collective skills of engineers and health-workers in developed countries. There has been a growing interest among professional and student engineers to solve global development issues, as evidenced by the rapid growth of organizations like Engineers Without Borders, and Engineers for a Sustainable World. Given these resources, and the fact that Internet and/or cellular technology are ubiquitous in nearly every country, there is an opportunity to develop tools that facilitate cost-effective collaborative design efforts. In fact, these design tools are starting to emerge (e.g. www.mondialogo.org and www.thinkcycle.org) but have yet to be tailored to design and transfer for AT.

1.4 OBJECTIVES

The objectives of the work proposed here are both academic and practical. From the academic perspective, the chronic failure of wheelchair technology transfer (WcTT) indicates that the process is not well understood, which implies that research in the area is necessary. The initial step of this research is to identify the important variables, which drive the success or failure of WcTT projects; this is possible by cataloging past projects and identifying the principle causes (which are linked to common variables) for their success or failure. Once these variables are known, it is then important to develop objective ways to measure them. For example, we can assume that one of the important variables to consider is whether a device is 'appropriate' for the environment (cultural, physical, and economic) in which it will be used. Without a measurement tool to evaluate how ‘appropriate’ a device is for an environment, we cannot objectively compare and contrast WcTT projects, and we cannot use this variable to help ensure that new or modified designs are appropriate for a region. In simple terms, one first needs to know *what* to measure, and then one needs to know *how* to measure it. The academic portion of the work proposed here helps identify *what* variables to measure, and gives examples of *how* to measure those variables.

Because WcTT is inherently a practical pursuit, the second objective of this work is to meet a practical need. As discussed above, there are many past and ongoing projects related to WcTT of manual wheelchairs to low-income countries. What has yet to be investigated or wholeheartedly attempted is the design and transfer of powered mobility devices (PMDs) such as ‘scooters’ or electric powered wheelchairs (EPWs). Because of the high cost of the power, drive, and control systems of PMDs, they have been almost exclusively developed and sold in high-income countries. Individuals in low-income countries, who need PMDs for functional mobility, either remain in a bed, or use a MWC and have an assistant or family member help them move from place to place. Thus, the practical objective of this work is to transfer a PMD to India, where there is a tremendous need for these devices.

The first objective of this work is identify the variables which influence the success or failure of Wheelchair Technology Transfer, and develop a WcTT framework showing how these variables interact.

The first objective of this work was accomplished through a literature review and expert assessment of the important variables affecting the success of WcTT projects. The model or framework that will be developed will demonstrate how these variables interact as well as propose general ways in which they can be measured. A particular variable of the model—

‘appropriateness’—is then explored more completely using a case-study of transferring a PMD to India.

The second objective of this work is to transfer a PMD to India

The second objective was accomplished through a design process that continually addresses the question of whether the device is ‘appropriate’ for users in India. One of the first and most important pieces of information needed for product development is an understanding of the target market. To estimate the PMD market in India, we collected anecdotal information from our collaborators, and also performed estimates based on the Indian National Sample Survey (NSS) [9]. We also calculated market estimates, similar to other authors [6], based on United States PMD market per capita. Assuming that a household which included a person with a locomotion disability would purchase a PMD if their disposable income allowed them to pay for the device of within 5 years (the expected PMD life), we calculated the size and value of the market for each of the following PMD prices: US$500, $750, and $1000. We also took into account any subsidy that a household may get from the Indian government for the device [23].

Based on conversations with ALIMCO and ISIC representatives, we believe the overall wheelchair market is, approximately, 8 Million individuals. According to the 2002 NSS [9] there were approximately 10.2 Million Individuals with locomotion impairments. Thus, 8 Million seems to be a reasonable estimate. We then assumed that of these 8 Million individuals 10% would benefit from a PMD (an estimate based on the percentage of individuals with mobility impairments who used PMDs in the US [34, 35]). Under these assumptions, we found that the potential market if the PMD was priced at US$500, $750, and $1000 was 113,000, 68,000, and 27,000 persons, respectively. Assuming all devices sold, gross market value of the devices would be 56, 38, and 27 million US dollars, respectively. Put into perspective of the US market, if the cost of the device was US$500, the number of PMD users in India would quickly grow to ½ the number of PMD users in the United States. We assume this is a conservative estimate, since as volume grows; the cost of the device may reduce. Additionally, our estimates are based on per-capita income, and do not include monies that may be sent to family members from overseas, or those from charitable organizations.

Because the market size is highly-sensitive to cost, the goal is to transfer or design the lowest cost device for India. Considering that PMDs in the US cost, on average $2000 [36, 37], it is unlikely that simply transferring these devices to India is a viable solution. In fact, there is a selection of EPWs available for purchase in India, which is imported from Taiwan, China, and Europe, but the costs of these devices are so prohibitive that few can afford them. While importing these devices has not proven effective, it may be possible to simply manufacture these previously-designed devices in India using locally available materials and components. Import costs (shipping and taxes), component, and possibly labor costs would be reduced with this approach—which would lower the price of the device in India. This may be a reasonable method for effective transfer PMDs to India, but the important question of whether these western-style devices are even "appropriate" for the user in their environment still needs to be addressed. Addressing this problem will help avoid the same pitfalls experienced when transferring depot style MWCs to India [10] where the majority went unused.

International Standards Organization (ISO), and the American National Standards Institute/Rehabilitation Engineering & Assistive Technology Society of North America Wheelchair Standards (ANSI/RESNA) [24-26] can be used to address this question. If these devices meet the above standards, it is assumed they meet the minimum level of safety and durability (but not necessarily the users' needs). A portion of the work described in this proposal is devoted to testing these devices using these standards.

Probably the most important step in the PMD design process is to test the device in real-world environments with the users themselves. Mulholland [32] performed focus groups in India to test her mobility device, which helped guide the design. A similar but more comprehensive approach must be taken to help guide the PMD design establish the viability of the device in India. One of the difficulties of these types of projects is that much of the design and testing is done away from the target region. This can prolong the product-design process since product designers typically need to make assumptions about the environment, the manufacturing techniques, raw material quality, and skills of workers who may manufacture the product. These assumptions may not always be correct, which could cause more design iterations than anticipated. This was our experience when transferring a MWC design to ALIMCO [3] (Chapter 2). The MWC prototype developed in the US met the ANSI/RESNA standards, but when manufactured by ALIMCO, it fell far short of the standards. This results inspired us to investigate the material properties of the steel available in India [38], which turned out to have significantly less strength (Figure 1)

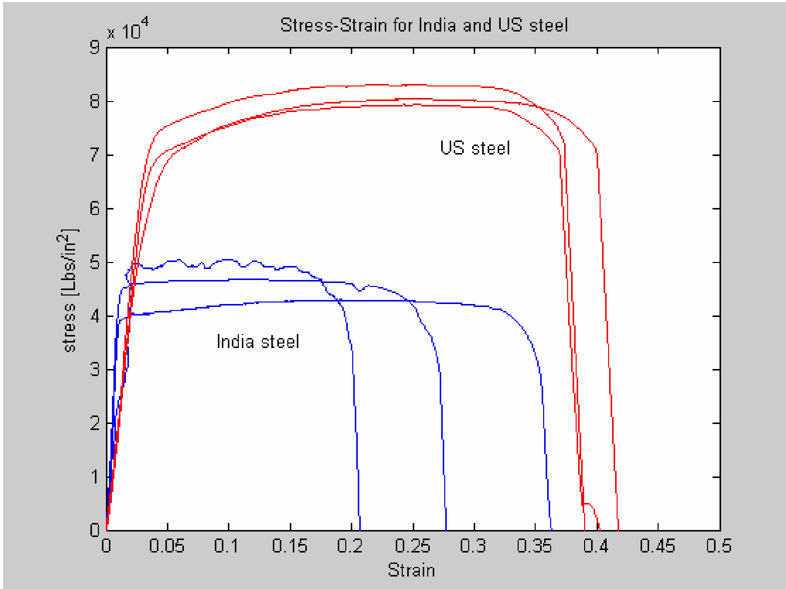

Figure 1: Stress-strain curves comparing Indian and US low-carbon steel strength

This example is specific to the material properties of steel in India, but extends easily to the other factors, which will determine if the device is appropriate in India. This includes whether or not the device meets the users needs in their home and community environment. This is not a new question—product designers constantly need to evaluate how a product can be designed or redesigned to meet the needs of the user in their environment. Focus groups are a common method used to address this question, but are difficult when designing and prototyping is performed in a remote location. Another, somewhat less-used approach is to have users document the unstructured environment in which they live, work, and play, and use this information to drive design. One low-cost approach is to ask people to document their experiences with diaries and/or disposable cameras [39]. This information can directly guide the design of a device, and also can provide information which can be used recreate aspects of the regions in where the device will be used. These recreations can be used to test the device (e.g., focus groups) in realistic and relevant environments, even if the testing is far from the device's targeted region. The work proposed here will demonstrate how this can be done effectively to inform and optimize the design of a PMD for India.

By addressing the PMD need in India with a well-documented and thorough design process, it is likely this device will be both appropriate and adopted. Furthermore, the model developed here, and the protocols used in this study, are not specific to India nor to PMDs; they will provide ideas and methods on how to best design and transfer these types of devices in the future to India and other regions.

2.0 TOWARDS THE DEVELOPMENT OF AN EFFECTIVE TECHNOLOGY TRANSFER MODEL OF WHEELCHAIRS TO DEVELOPING COUNTRIES [3]

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2.1 INTRODUCTION

The estimated number of potential wheelchair (WC) users in developing countries is from 20 – 100 million people ([6] and [7] respectively) of which an estimated 95% [40] do not have access to them. This overwhelming and growing problem has been addressed over the past several decades by dozens (if not hundreds) of projects trying in different ways to transfer and/or deliver wheelchair technology to these nations. These projects can be generally categorized into charitable efforts or small-scale workshop efforts.

Charitable efforts transfer wheelchairs to developing countries on a cost-free basis to meet the need in these countries. The wheelchair type, the mode of distribution, and the level of service delivery (seating, fitting, etc.) all vary widely among these groups. In general, new or refurbished 'hospital' type wheelchairs are distributed in these countries (e.g., Wheels for the World (WFW [41]), Hope Haven International Ministries (HHIM [42]), Wheels for Humanity (WFH [43]). In other cases, such as with the Wheelchair Foundation (WCF), efforts are made to re-design wheelchairs to be more appropriate for developing countries. In this case, the wheelchairs are mass-produced in a third-party country (China, for example) and are then distributed in the target country.

In some cases, the fundraising side of the efforts and the distribution are separate, as with the WCF. In this case, the distribution and service delivery is provided by religious and secular organizations either in the target country or who travel to the target country and distribute the wheelchairs. In other cases, a single group, such as the WFW, HHIM, or WFH performs the fundraising, wheelchair purchasing/refurbishing, and delivery. Being involved directly in the service delivery allows these groups to maintain a higher quality of service delivery, such as specialized seating services, that are important when providing a wheelchair. With WFW, HHIM, or WFH, specialists who are part of the distribution team provide these services. When distribution is separate, as with WCF, service delivery quality can vary depending on the group delivering the wheelchairs. According to the websites of these organizations, they have provided a total of nearly 400,000 wheelchairs to people in developing countries (WFH 16,000, WFW 20,000, HHIM 42,000, 311,000 WCF [41-43]).

The wheelchair workshop model was pioneered by Whirlwind International [6, 20, 22, 30, 44], and continues to help maintain and establish wheelchair workshops in developing countries. The goal of these projects is to start self-sustaining workshops in developing countries to build and improve wheelchair designs. These projects have been successful to varying degrees—some workshops are self-sufficient while others have failed. In 1990, an estimated 25 workshops were operating in 18 countries [6]. The number of factories has grown, and the estimated cumulative number of wheelchairs produced by these factories since their inception is approximately 50,000 [45].

According to the estimated numbers above, the efforts to start workshops and distribute donated wheelchairs have cumulatively provided less than ½ million wheelchairs to developing countries over the past *several decades*. In 1990, an estimated one million wheelchairs *per year* were needed if the supply of wheelchairs was going to meet the demand by the year 2020 [6]. Fourteen years after this estimate, there is still a staggering and growing need for wheelchairs. Even in India, current estimates suggest there are over ten million people who need wheelchairs, and production is less than 20,000 units/year [27] from their largest supplier. More discouraging is that the above estimate of half million does not take into account the lifecycle of a wheelchair, which is estimated to be five years. Thus, less than half of the wheelchairs provided, or one quarter million wheelchairs may still be operational today.

The hard work of individuals involved in these projects is admirable, and the substantial amount of money donated to carry out these projects has had an impact, but more must be done to meet the need for wheelchairs [6, 7, 19, 20, 22, 30, 44, 46-48]. By understanding the positive and negative characteristics of the projects presented above, and investigating other mechanism for technology transfer, a more guided and effective approach may be possible. With the many separate groups interested in providing wheelchairs for to developing countries, including the charitable organizations, governments of developing countries, and organized groups of engineers and clinicians (such as the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) SIG 17), a more guided effort could quickly improve the efficiency and effectiveness of wheelchair provision.

The purpose of this paper is to develop a framework describing wheelchair tech-transfer to developing countries. This is an important step in integrating what has been learned from previous approaches with current and potentially viable approaches for the future.

Ultimately, from this framework, objective measures can be developed to compare past and present approaches so that this important data can be effectively used to guide future approaches.

2.2 METHODS

We developed a list of possible models for WC tech-transfer to developing countries. This list is comprised of models widely used, one model that we used to transfer wheelchair technology to India, and other models we hypothesized are viable means to transfer this technology to developing countries.

To expand on the widely used models of charitable distribution and the small-scale workshops, we performed a literature review. While we expect details of all projects are not reported, the available literature describing the projects gives a general overview of their positive and negative attributes. Furthermore, we expand on these models based on our own experiences; two of the authors (RAC & JP) have been involved with workshop model projects (both hands-on and coordinating with the project leaders). All of the authors are experienced with the types and quality of the wheelchairs provided through charitable donation model and one (JP) has been involved in the distribution and modification of these wheelchairs.

To expand on the 'manufacturing model' that we introduced into the framework, we discuss an ongoing project we have with a large-scale assistive technology manufacturing facility in India. Throughout this project, we have documented the progress and the various drawbacks and requirements to make it a success. We present an overview of our approach based on our experiences.

To demonstrate that the other tech-transfer models we have integrated into the model (specifically, multi-modal and globalization) are viable, we present examples where they could be appropriate, or where they are established, but not formally organized as a tech-transfer approach. The examples are reasonable and are justified based on the combined expertise of the authors in areas of service delivery, manufacturing, engineering, and assistive technology.

In the final portion of the paper, we present a framework that highlights the various aspects of the technology transfer process and compares them using language common and measurable to all models. This framework is based on the literature review we performed and our own experience in transferring WC technology to developing countries.

2.3 RESULTS

2.3.1 Developing a list of Technology Transfer Models

Primarily two mechanisms have been used to transfer wheelchair technology to developing nations: small-scale workshops and distributing donated wheelchairs. Other mechanisms are possible, but have not been described at length, or demonstrated in practice. We present a list of a total of five mechanisms (Table 1), with a short discussion of the attributes of each.

Table 1: Description of five potential wheelchair technology transfer mechanisms to developing countries.

Model	Delivery Mechanism	Cost	Sustainability	Impact
Charitable	Provide wheelchairs through regional distribution points.	The cost scales with the number of wheelchairs provided, although there is some economy of scale. Labor costs are often minimized by using volunteers.	Low sustainability. Often depends upon a single individual or small group driving the process. Donations must be constant.	Immediate and potentially large. A large number of wheelchairs can be delivered in a short period of time.
Workshop	Train individuals in the country in need of wheelchairs. Small-scale workshops are set-up for wheelchair construction.	The costs for this approach are low, and the mechanism can be used to transfer technology one workshop at a time as resources permit.	Moderate sustainability. Workshops must survive from donations or the sale of the wheelchairs. In some cases, income is supplemented with other complimentary products (e.g. bicycles)	Immediate but typically low impact (except in the immediate vicinity of the workshop). Local personal may become employed.
Manufacturing	Train local individuals in the manufacture of wheelchairs. Set-up a factory on a large-scale, with regional or national distribution.	Work with local governments preferably with foreign aid agencies to defray costs of setting-up factory. Wheelchair costs paid by government, foreign aid, individuals/families or charities.	High sustainability. Factory would help to establish industry and support healthcare professionals. Would establish a product line, spare parts, and local service.	Long-term, but potentially very large. Could create an industry to design, manufacture, and delivery of wheelchairs.
Globalization	Established company expands into a region either by establishing a factory or by importing product.	The costs to the region are typically low, with costs covered through the sale of the product.	High sustainability. Factory would help to establish industry and support healthcare professionals. Would establish a product line, spare parts, and local service.	Near and long term. Can be very large, bringing proven products to the market.
Multi-Modal	Combines aspects of all of the models above to meet the needs of people with mobility impairments in the region.	The costs could be ramped-up with the resources available. The model would allow the scale to expand as resources became available	Potentially highly sustainable if the resources are well managed and a solid business plan is put together.	Maximum impact. The manufacture, distribution and delivery would cross the spectrum from local to national.

2.3.2 Examples

Charitable Model: The Wheelchair Foundation (WCF) collects donations from around the world, though most donations come from the United States of America. These funds are used to purchase wheelchairs from China that are made to the WCF's specifications. These wheelchairs are then shipped to key distribution points in the countries targeted by the WCF.

Workshop Model: Whirlwind Wheelchairs International (WWI) and its affiliates have developed materials to help local blacksmiths or bicycle repair shops construct wheelchairs. A notable component of the WWI program is that volunteers are trained in the design and construction of manual wheelchairs prior to going into the field. Typically, new assistants are paired with more experienced individuals for their first few visits.

Manufacturing Model: The University of Pittsburgh has taken this approach through its collaboration with the Artificial Limbs of India Manufacturing Company (ALIMCO). ALIMCO was an established manufacturer of prosthetic limbs and other walking aides. Through their collaboration, an adjustable adult manual wheelchair was developed, and is in the process of going into manufacture.

Globalization Model: Invacare Corporation and Sunrise Medical have begun manufacturing components, and, in some cases, entire wheelchairs in China. Similarly, Invacare has a facility in Mexico: (Invamex) in Reynosa, Mexico. Wheelchairs manufactured in these facilities are built for import into the U.S.A. and Europe; however, the products are available elsewhere. Because these wheelchairs are manufactured in developing countries, distribution costs would be lower and possibly make these wheelchairs more affordable for local populations. Furthermore, because of their proximity to large demand of wheelchairs in these regions, these companies may be in a strong position to capture the market. Encouraging these companies to re-design their wheelchairs to be appropriate for the local environments and for a price that is not prohibitive to the local population (or their government) may be the key to establishing a strong globalization model.

Multi-Modal Model: India is probably the best example of a multi-modal market, although it is not coordinated and probably not by design: India has local manufacturers (e.g. ALIMCO), blacksmith level construction, and distributors who import wheelchairs from European, American and Asian manufacturers.

2.3.3 Expanded Examples: The Manufacturing Model

Our labs have an ongoing relationship with ALIMCO, the largest assistive technology producer in South Asia. Because of the ALIMCO's established manufacturing facilities, this project naturally falls into the manufacturing model described above. To gain a better understanding of this model, we have documented our relationship and progress on the project so that, if ultimately successful, it can be a guide to future projects.

Project Overview:

The partnership between HERL and ALIMCO was facilitated through the National Institute for Disability and Rehabilitation Research (NIDRR) in 2001. Because NIDRR had an existing relationship with ALIMCO (by establishing other consulting partnerships), the initial contact was facilitated quite easily. HERL Engineers and clinicians traveled to India in December 2001, and met with the leadership and engineers at ALIMCO. During this meeting, rapport was established, and immediate consulting services were provided and long-term consulting goals were established.

The immediate consulting services stemmed from touring ALIMCO facilities and reviewing their wheelchair designs. HERL engineers provided advice to ALIMCO on methods to improve their wheelchair design based on manufacturing and design improvements. This advice included:

1. Make axle position adjustable on their manual wheelchair.
2. Upgrade tooling equipment (EDM, CNC) so higher-grade jigs could be made.
3. Develop a testing protocol to improve quality control.
4. Incorporate document control and intermediate quality checks.

The above advice was meant to make immediate improvements to the quality of ALIMCO's manual wheelchairs without requiring major product design modifications. In parallel with these immediate consulting services, a long-term goal was agreed upon to systematically expand and upgrade ALIMCO's product line so that the products met industry standards, and thus would more safely meet the needs of the their consumers. The long-term goal, broken down into three phases was:

Phase I:

a. Setup an ANSI/RESNA wheelchair testing lab.
b. Introduce a wheelchair testing protocol (based on ANSI/RESNA standards).
c. Upgrade the manual wheelchair design—reduce weight and increase adjustability, so the wheelchair could be adjusted to fit the user.

Phase II: Design and transfer a cost-effective tilt-in-space pediatric wheelchair

Phase III: Design and transfer a cost-effective, durable power wheelchair

Our overall model for design and technology transfer portion of our projects (Figure 2) includes (1) and initial ANSI/RESNA testing phase (when a product, such as the adult manual wheelchair already exists); a (2) product (re)design phase; (3) a tech-transfer phase, where we deliver the produce to ALIMCO and demonstrate how it is built; and (4) a small production run phase. Once this small production run is completed, HERL performs ANSI/RESNA standards testing on the product, and ALIMCO performs human testing on the product. If both of these tests demonstrate the product meets industry standards and the needs of the consumers, it is put into full production. If these criteria are not met, the design is upgraded and the tech-transfer and testing phases are performed again (although design changes have been minor and not required a complete re-design).

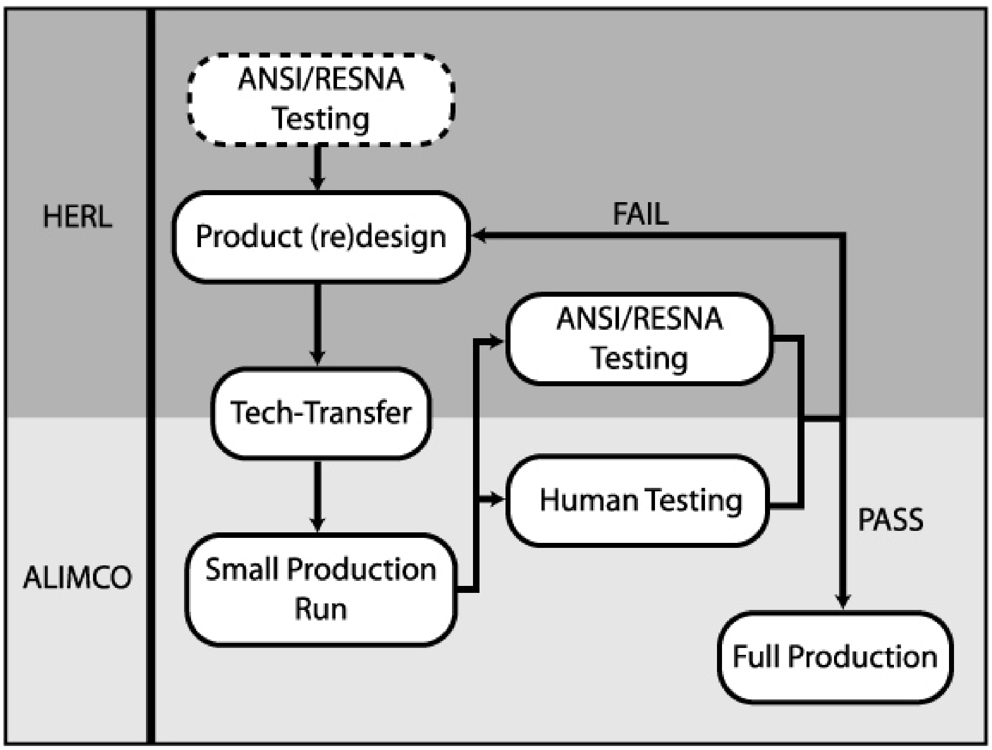

Figure 2: Manufacturing Model Tech-Transfer Flowchart

Currently (November 2004) the majority of Phase I has been completed (only slight modifications on the new adult-manual wheelchair are being made) and we have begun Phase II. Based on our experience with Phase I, we have realized the ANSI/RESNA testing after the small production run is critical to ensure manufacturing and material quality are maintained to the levels of those transferred. Our experience demonstrated that manufacturing shortcuts and sub-standard material quality can significantly affect the durability of the wheelchair and design modifications must be made to account for the material and manufacturing quality.

Based on this experience in Phase I, we are performing testing to determine the material properties and quality of the Indian material. These tests include Rockwell hardness tests, tensions tests, finite element models, and comparison of U.S. and Indian material standards. A more complete understanding of the Indian material will help us avoid durability problems when the wheelchair is manufactured at ALIMCO, helping to optimize the technology transfer. Likewise, we have become more focused on providing go-no-go jigs, and establishing strict standards for material and manufacturing quality to assure the product is of high quality. Recent upgrades to ALIMCO's manufacturing facilities such as wire-feed welding and plastic injection molding machines has allowed us to design the pediatric wheelchair with these methods in mind, which increase strength, quality, and manufacturing speed.

The success of the HERL-ALIMCO partnership will ultimately be gauged by the number and quality of wheelchairs manufactured by ALIMCO. In part, this will be a function of how streamlined and effective the design and technology transfer approach is that we use (Figure 2). Other factors leading to the success of this project are non-technical, and related to the coordination and efforts of NIDRR and thus the US Government to improve assistive technology worldwide. The importance of these factors should not be overlooked, since they are critical to coordinating such efforts in the future.

Important Factors that led to the HERL-ALIMCO partnership were:

(1) NIDRR had an existing relationship and provided initial support

(2) Funding mechanisms such as provided through the Rehab Act of 1973, and the Agricultural Trade Development and Assistance Act of 1954 (Public Law 480) have provided funding for the project.

(3) ALIMCO already had a mobility product line and basic manufacturing capabilities.

(4) The leadership of ALIMCO and HERL developed a quick rapport, which encouraged closer collaboration.

(5) India has a tremendous need for mobility devices, especially wheelchairs. Other technology transfer models were either unlikely to be effective or not within our means.

(6) The U.S.A. and India were/are willing to support the HERL-ALIMCO collaboration financially and logistically by organizing meetings and contact through the U.S. Embassy in India (through support from the U.S. State Department).

(7) The government of India (via ALIMCO) has provided logistical and financial support.

While all of these factors may not be critical for successfully using the manufacturing model of technology transfer, they are important for the success of the project. Thus, these factors are an important difference between the charitable distribution model, where the product is just shipped in, and little collaboration in the target country is necessary, or the workshop model, where successful transfer may only require collaboration among a few people in the community where the workshop is to be started.

Another project that follows the Manufacturing model is the Wheelchairs for Afghanistan (WFA) project (www.cirnetwork.org/engineering/wheelchairs.cfm and [49]). The WFA project focuses on distributing appropriately designed wheelchairs (based on Whirlwind International's original design) [22], which are manufactured in a medium-scale production facility in India, to people with disabilities in Afghanistan; because this project is recent, no clear outcome is known yet. Even without outcome information (which is difficult to find for all models) [48], this model provides much hope by balancing the positive aspects of the workshop model (appropriate design) and charitable distribution model (large volume).

2.3.4 A Technology Transfer Framework

To compare each of the models based on factors relevant to the success of projects using these models, we have established the following broad definitions describing the important factors in the technology transfer process, and a diagrammatic representation (Figure 3).

- Input: The financial and/or technical requirements necessary to perform the project.
- Sustainability: The ability of the project, after completed, to have established wheelchair production that does not require persistent external input. This could also include the economic value to the local community generated because of the project (e.g., developing jobs, income into a region, educational benefit by training workers, etc.).
- Appropriateness: A metric describing how well the wheelchair fits the need of the consumer in his/her cultural, physical, and psychosocial environment. This could be measured by the average number of years wheelchairs functions properly, abandonment rates, and/or maintenance rates.
- Impact: The number of wheelchairs produced and or delivered in a given period of time.

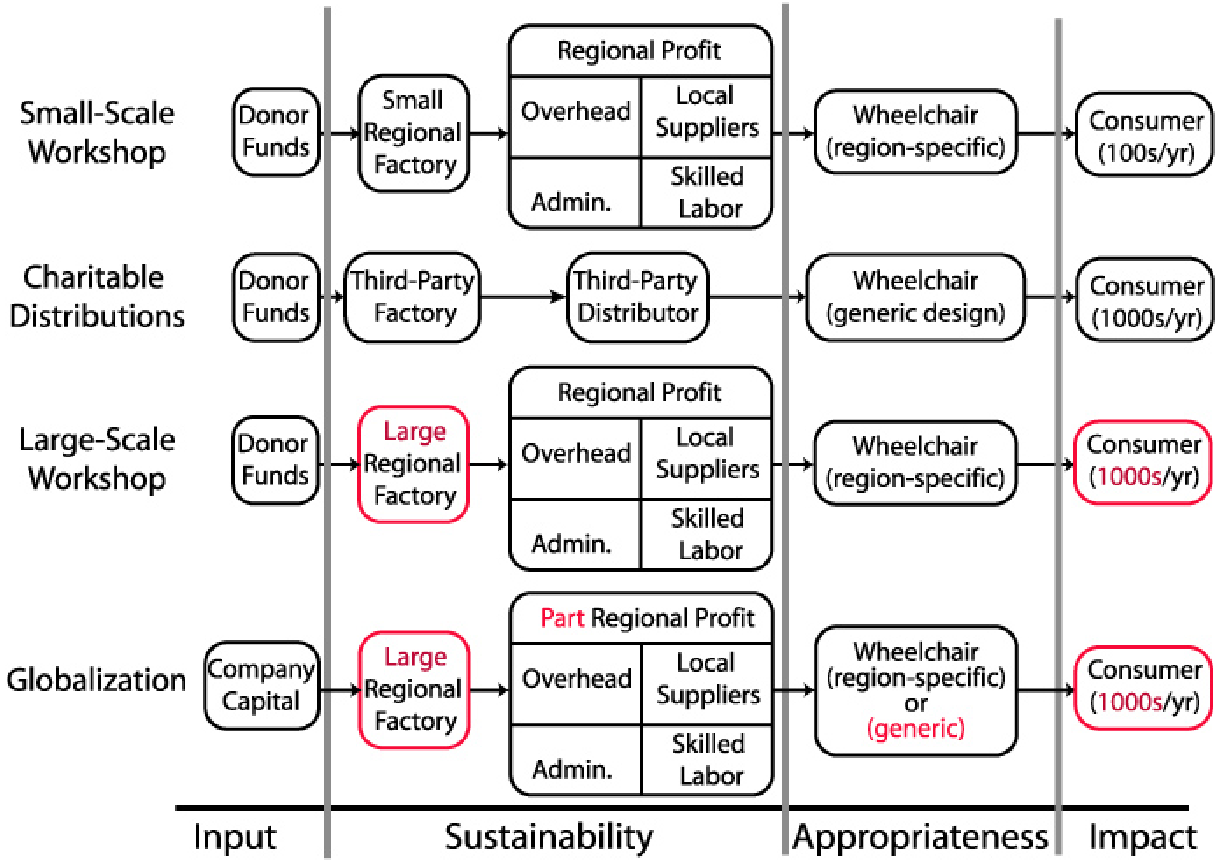

Figure 3 Technology Transfer Framework; Multi-modal is a combination of the above models.

We use the above language because each of the four factors (input, sustainability, appropriateness, and impact) have all been deemed important factors in both measuring the success of a project and evaluating whether one should be started. By combining these metrics one could, for example, compare the cost per wheelchair delivered (impact/input) between projects. Similarly, one could develop a metric for local impact (sustainability/input i.e., #jobs developed/input cost). The diagram (Figure 3) allows for simple comparisons between the different models based on their input, sustainability, appropriateness, and impact.

2.4 DISCUSSION

We took an important step by developing a comprehensive framework for WC tech-transfer to developing countries. An earlier literature review [2] focused on qualitative evidence, but have fallen short of looking at the WC tech-transfer problem systematically. In this review, we described a range of possible models to transfer WC to developing countries, and provided examples of each. Furthermore, we provided expanded examples of the charitable distribution, workshop, and manufacturing models based on published articles, and based on our own experiences.

Because the workshop model encourages appropriately designed wheelchairs and supports the local infrastructure (i.e., has moderate sustainability), it is typically considered the most beneficial model for the transfer of wheelchair technology [50]. The drawback to this model is that it is not easily scalable, and the liveliness of the workshop depends on the local economy and the constant demand for the product; furthermore, quality of the product can vary depending on the level of training of the workers and fluctuation in the quality of the raw materials.

The charitable distribution model is generally seen as a quick model to provide a large volume of wheelchairs to a target region. This is a very effective model in the case of sudden need (i.e., following a war), but critics suggest it is not a sustainable model for transferring wheelchairs, because the wheelchairs are not typically appropriate for the targeted region. Improving the design of these wheelchairs to be regionally appropriate, and ensuring that the wheelchairs are equipped with appropriate and special seating services would improve this model of technology transfer.

The HERL-ALIMCO partnership, which uses the manufacturing model, demonstrates a unique way to transfer WC technology. In this model, experts from HERL perform a consulting service for ALIMCO. The virtues of this consulting mechanism given the financial backing can be easily duplicated with other companies in developing countries. The primary limitations are (1) few manufacturing facilities such as ALIMCO exist, and (2) precautions need to be taken to ensure that the manufacturing and material quality do not compromised the transferred design. As shown above (Figure 1) we have independently tested wheelchairs manufactured by ALIMCO after the design has been transferred to make sure the wheelchair, as built by ALIMCO, conforms to the ANSI/RESNA standards. Without this extra testing component of our consulting relationship, the upgraded design could potentially perform worse than the product they currently manufacture.

Globalization offers a promising means for an established company to expand their market while providing wheelchairs for those who need them. An obvious difficulty with this model is cost-control; those who need wheelchairs are typically the poorest in a developing country, thus paying for the wheelchairs is impossible. Some governments subsidize the costs of wheelchairs, like India, but these subsidies would not cover the $500+ cost of a manual wheelchair. Thus, to make up the cost-gap, manufacturers would have to design lower-costing wheelchairs, and/or other subsidies would have to be found.

The multi-modal model may be established in several countries, but in an unorganized manner. A more complete understanding of the wheelchair providers in a particular country or region must be known before a formal evaluation of the multi-modal model can be performed. One can imagine that balance between large-scale and small-scale suppliers would provide an appropriate balance of custom wheelchairs and low cost. With a multi-modal analysis, one could evaluate this market balance in a particular region.

This review was based on published literature and the experiences of the authors. We assumed that the published literature represents only a small fraction of the total projects undertaken. This limitation is important, as it suggests the important information about the pitfalls and benefits of projects are not reported. We also limited the search to the English language, although there may be relevant publications in other languages.

Provision of wheelchairs to people in developing countries has not been an academic interest—it has mainly been the interest of charitable foundations, and grass-roots organizations starting workshops. One author has suggested an outcome study of wheelchair provision to developing countries would be informative [48], but none have been reported. Part of the goal of the present study was to standardize the language used when discussing these technology transfer projects. A critical first step in evaluating the success of these projects is to develop a common language; the second step is to develop objective measures so past projects and current projects can be evaluated. These metrics should evaluate projects based on their input, sustainability, appropriateness, and impact. Developing these metrics is a focus of our current work, and we will use these metrics to evaluate past and present projects. This way, future projects can be guided from objective evidence, rather than anecdotal stories from persons who may have emotional bias [50] as to the best way to provide wheelchairs.

2.5 CONCLUSIONS

With the reportedly 20-100 million ([6] and [7] respectively) people in need of a wheelchair worldwide, the problems of wheelchair provisions in developing countries is enormous. To tackle this overwhelming need requires the efforts of many people, organizations, and governments [19, 51, 52]. Past efforts have been largely uncoordinated [48], and in some cases have created divides among project leaders aiming to solve the same problems [50]. To solve this problem, objective measures of outcomes must be made, and ultimately, used to guide the successful transfer of WC technology to developing countries. Without taking this important next step of learning from our mistakes and collaborating with one another, the fractured efforts will likely continue (some helping, some hurting) and the overwhelming and growing need for wheelchairs may never be met.

2.6 ACKNOWLEDGEMENTS

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3.0 EVALUATION OF THE SAFETY AND DURABILITY OF LOW-COST NON-PROGRAMMABLE ELECTRIC POWERED WHEELCHAIRS [53]

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3.1 INTRODUCTION

The American National Standards Institute/Rehabilitation Engineering and Assistive Technology Society of North America (ANSI/RESNA) wheelchair standards [24, 25] (the United States version of the International Standards Organization (ISO) standards) allow clinicians and their patients to objectively compare and contrast wheelchairs to identify the most appropriate product. This becomes increasingly important when wheelchair reimbursement by insurance providers (such as Medicare) is limited; clinicians and their patients aim to identify the best wheelchair for their needs within the allowable set by the insurance company.

Safety and durability are critical factors when choosing an electric-powered wheelchair (EPW). Safety issues, such as stability, maximum speed, and braking distance are important factors that can either contribute to or prevent the common tip- and fall-related injuries [54].

Durability of the wheelchair should be sufficient enough that it does not fail within a 3-5 year period: the typical time span Medicare (and thus other insurance companies) expects wheelchairs to last before they will fund a replacement. Factors that determine wheelchair durability include the ability to withstand static, impact and fatigue loading conditions, controller and charger wiring malfunctions.

While the US Food and Drug Administration (FDA) requires each wheelchair put on the market to pass the ANSI/RESNA standards, testing by independent laboratories are not required. Thus, when the manufacturer performs these evaluations, bias or misinterpretation of the ANSI/RESNA standards may lead to improper outcomes. Previous studies have demonstrated that both Electric Power Wheelchairs (EPWs) [55, 56] and manual wheelchairs [13, 14, 57] on the market do not necessarily pass the ANSI/RESNA testing standards when tested independently. The least expensive of the manual wheelchairs (depot-style) has been shown to fare worst overall [14], which makes it especially important to test this class of wheelchairs. Furthermore, neither the US FDA nor Medicare currently has the resources (such as independent laboratory tests) to verify that the manufacturer's testing methods are correct.

The low-cost power equivalent to the depot-style manual wheelchair is the low-cost, non-programmable EPW. These EPWs have standard 'captain's chair' seating systems, and do not offer programmable controllers (the primary difference between these low-cost EPWs and the next higher grade). In the United States, Medicare reimbursed for over 26,000 of the low-cost non-programmable EPWs from 2000-2003, and while they reimburse for several fold more next higher grade EPWs (more than 600,000 over the same period [36, 37, 58]), no ANSI/RESNA standards test results on the currently available low-cost non-programmable EPWs have been published. Studies published on the higher grade EPWs have shown that durability is generally high [55, 56], but there is no evidence that this is the case for these low-cost EPWs.

Identifying if and what shortcomings exist in these low-cost EPWs is becoming increasingly important in the US, in particular, given the recent EPW coding changes proposed by Medicare (which are generally followed by other insurance providers) in combination with the competitive bidding strategies that may be instated soon [59]. Proposed coding changes include requiring all EPWs to have programmable controllers, which would require manufacturers to upgrade the low-cost EPWs with a higher quality controller [60]. No specific requirements have been made on the upgrades to the underlying frame, drive train, or seating systems. Considering that competitive bidding for EPWs is likely in the near future [59], manufacturers may choose to base future model designs on the low-cost EPWs to limit costs, and thus be more competitive against other manufacturers. If safety and/or durability problems exist in these low-cost EPWs then it is important to identify and correct them before they are transferred to upcoming models. Furthermore, these issues are not isolated to the US; since healthcare costs are rising worldwide, and associated cost-cutting measures may negatively impact device quality and consumer safety.

To evaluate the safety and durability of low-cost non-programmable EPWs independently, we performed ANSI/RESNA standards testing on a selection of these low-cost EPWs. We performed this study in part to present independent informative data comparing and contrasting a selection of these EPWs. We also sought to compare these low-cost non-programmable EPWs to the higher-cost and higher-grade EPWs previously tested and discussed in the literature [55, 56]; we make this comparison specifically based on the durability measures (equivalent cycles) and related value (cycles/$) for these and the higher class EPWs.

3.2 METHODS

We performed ANSI/RESNA wheelchair standards tests on 3 identical low-cost, non-programmable EPWs from a total of 4 manufacturers (n=12). The following wheelchairs were tested: Pride Mobility (PRMO) Jet 10, Invacare (INVA) Pronto M50, Electric Mobility (ELMO) Rascal 250PC, and the Golden Technologies (GOLD) Alante' GP-201-F (Figure 4). Of the several low-cost, non-programmable wheelchairs on the market, we chose to test models offered by the largest manufacturers to ensure that the results would be relevant to the largest population of potential and current users. The wheelchairs were purchased through a third-party purchaser to ensure that we received a random sample of the wheelchairs from the manufacturers.

Figure 4 EPWs tested. From top left clockwise: ELMO, INVA, GOLD, PRMO

We followed the methods required in the ANSI/RESNA wheelchair standards explicitly, and performed all tests required for EPW with the exception of sections 16 and 21 (ignition of upholstery and electromagnetic compatibility, respectively), because our laboratories are not equipped to complete these sections.

For convenience, we tested all wheelchairs according to methods required for a specific section before starting another section. Within a given section, we randomized the order a particular wheelchair was tested to wash out any sequence effects. In sections 14 and 8 (Power and Control and Static/Impact/Fatigue, respectively), we broke from this protocol and performed tests simultaneously on several (randomly ordered) wheelchairs in the interest of saving time.

While the methods are published in the standards, we will briefly describe each section, and any statistical methods beyond descriptive statistics we used to analyze and present the data (the standards do not specify statistical methods, only testing methods):

Static Stability (Section 1) is performed by placing the wheelchair with 100 kg test dummy on a test-ramp, and changing the inclination of the test ramp until the angle is found where the EPW will tip (Figure 5). This angle is recorded with the wheelchair setup in the most and least stable configurations for the forward (wheels unlocked and locked), rearward (wheels unlocked and locked) sideways (left and right sides down slope) and on the anti-tippers (either front or back); in total, 14 measurements were recorded. A one-way MANOVA (main effect: EPW model) was performed on the tip-angles for the forward, sideways, and rearward direction with the wheelchair in the *least stable* condition, and using the dependent variables, which described when tires would initially lose contact and cause loss of control of the EPW.

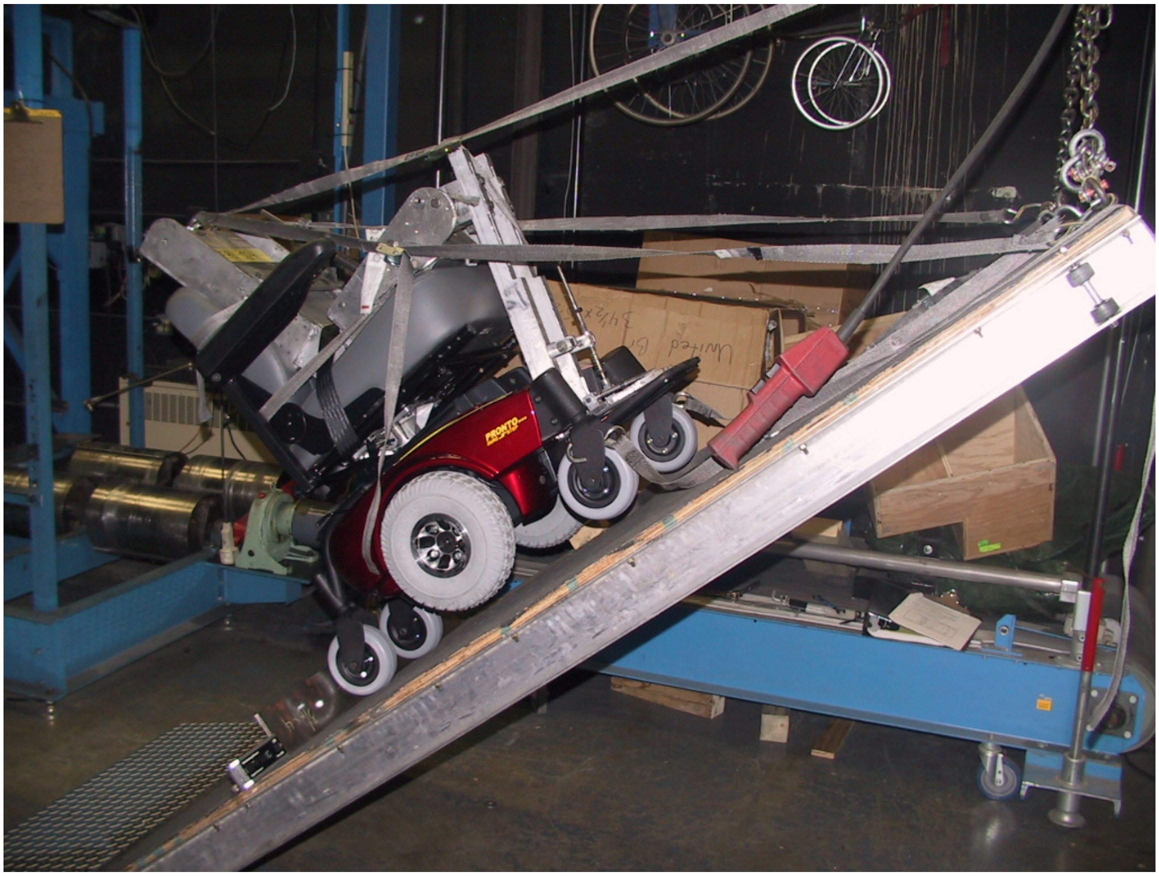

Figure 5 Static Stability Testing (rearward direction)

Dynamic Stability (Section 2) is performed by evaluating the response of the EPW to dynamic tasks while traveling on a 0, 3, 6, and 10 degree test plane. Responses are coded with a score from 0 to 4, which indicated if the EPW tipped completely (0), became stuck on the anti-tipper (1), performed a transient tip and the anti-tippers touched the ground (2), performed a transient tip (3), or did not tip at all (4). These codes were recorded for 31 tasks, including: starting and stopping traveling upward and downward, while turning, and when traveling up and down a step transition of 12, 25, and 50mm. For the majority of cases, a human test pilot maneuvered the wheelchair unless the expected response may be dangerous for the rider. In these cases, a 100kg test-dummy was secured to the EPW while a human operator walked or ran beside the EPW. All trials were performed at maximum speed. To compare dynamic stability scores across manufacturers, a Kruskal-Wallis test was performed, and if significant differences were found, pair-wise Mann-Whitney U tests were performed.

Effectiveness of Brakes (Section 3) are evaluated by measuring the braking distance of the EPW while traveling on a 0, 3, 6, and 10 degree test plane in both the forward and reward direction. Three braking modes were evaluated: normal joystick release, joystick reverse, and power off. In total, 72 data points were collected for each EPW. A repeated-measures ANOVA and Tukey's post-hoc (where appropriate) was used to distinguish if EPW had significantly different braking distances for each condition.

Energy Consumption (Section 4) is reported as the theoretical range a particular EPW can travel before it depletes the batteries. By measuring the depletion of a fully charged battery (E ampere-hours), with a known capacity (C ampere-hours) while traveling a known distance (D meters), the theoretical range can be calculated (R km) by the following equation:

$$R = \frac{C * D}{E * 1000}$$

Climatic Testing (Section 9) is performed by exposing the EPW to five adverse environmental conditions including long- and short-term heating and cooling, and water to simulate conditions which may occur during normal use, shipping, or storage. After environmental exposure, each EPW is maneuvered through a test-track and adverse behaviors are recorded (if it does not maneuver correctly, it fails this section). Adverse behaviors and other reasons the EPW would fail the test include: (1) any behaviors deemed dangerous by the tester,

2) the time taken to drive around the test track is greater than 60 seconds, (3) the wheelchair fails to stop, or (4) the wheelchair moves when not commanded to.

Static, Impact, and Fatigue (Section 8) testing is performed by applying static and impact loading conditions to parts of the EPW (arm rests, foot rests, wheels, shrouding) and by testing the fatigue life of the whole wheelchair. Fatigue life (also referred to as durability) is tested using double-drum (DD) and curb-drop (CD) testing machines. Scores in Section 8 are based on whether the EPW passes or fails the given test; for the fatigue testing, the EPW passes the test if it endures 200,000 DD and 6,666 CD cycles (which is equivalent to 3-5 years of use). We mounted an additional drum on the double-drum testing machine when testing the Invacare Pronto M50 because it has 6 wheels simultaneously on the ground (Figure 3). This modification has been suggested for future versions of the ISO Wheelchair Standards, but has not been formalized[14]. All values are reported with descriptive statistics. Additionally, equivalent fatigue life cycles were calculated using the following equation: Equivalent Cycles=DD cycles+30*(CD cycles) [13, 14, 55] and were compared using a one-way ANOVA (main effect: EPW model). If main effects were significant at $\alpha=0.05$ level, a Tukey's post-hoc was performed. Value, defined as the number of equivalent cycles per dollar, was also calculated by normalizing the equivalent cycles by the retail price of the EPW.

Figure 6: Example of the double-drum durability testing machine (modified to test the 6-wheeled Invacare)

Power and Control Systems (Section 14) are evaluated through a series of tests on the joystick, controller, battery charger, battery wiring, and drive motor wiring. These tests evaluate the response of the power and control system to events due to user or maintenance errors (such as stalling the wheelchair, or reversing the polarity of the battery wires) or events resulting from wear-and-tear, such as short-circuiting (due to insulation wear). All adverse behaviors that are potentially dangerous are reported.

3.3 RESULTS

Static stability results (Table 2) are presented for the least-stable EPW setup. The locked forward and rearward condition and anti-tip condition was not applicable for the INVA (Figure 4) because it is a mid-wheel drive EPW with front and rear casters which are always in contact with the ground. Thus, tipping angle is insensitive to whether the drive wheels are locked or unlocked since it is measured when the drive wheels initially lose contact with the test plane. The GOLD and PRMO EPW have rear-casters, and the ELMO EPW has front casters, and thus the rearward and forward locked conditions were not applicable, respectively.

Table 2: Mean (standard deviation) static tipping angles (degrees) for each direction and condition for the least stable setup. *Italicized* values were used in the MANOVA, and superscripts (a-d) represent significant groupings based on a Tukey's post-hoc test for each direction (forward, rearward, and each sideway direction); Group a is the group with the highest tipping angle (most stable) and b, c, and d are lower tipping angle groups.

Direction	**Forward**		**Rearward**			**Sideways**	
Condition	**Lock**	**Unlock**	**Lock**	**Unlock**	**Anti-tip**	**Left**	**Right**
EPW							
GOLD	*20.1* ^{b} *(0.9)*	25.1 (1.3)	*	*27.6* ^{c} *(0.6)*	29.1 (1.3)	*22.3* ^{a} *(0.3)*	*23.7* ^{a} *(0.4)*
PRMO	*2.5* ^{c} *(0.6)*	17.9 (0.3)	*	*35.6* ^{a} *(0.9)*	26.8 (0.6)	*23.8* ^{a} *(1.3)*	*22.7* ^{a,b} *0.2)*
ELMO	*	*32.6* ^{a} *(4.5)*	*6.6* ^{d} *(1.0)*	8.2 (1.7)	16.9 (2.3)	*22.7* ^{a} *(0.4)*	*23.6* ^{a} *(1.3)*
INVA	*	*13.4* ^{b,c} *(2.8)*	*	*30.5* ^{b} *(0.4)*	*	*19.0* ^{b} *(1.7)*	*20.4* ^{b} *(1.7)*

A MANOVA was performed using dependent variables related to when the user would likely lose control of the EPW in any of the four tipping directions. The left and right sideways tipping angles were used for all EPWs. The 'lock' condition was used for the forward direction, and the 'unlock' condition for the rearward direction for both the GOLD and PRMO EPWs. The ‘unlock’ condition was used for the forward direction and the ‘lock’ condition for the rearward direction of the ELMO. For the, INVA EPW, the ‘unlock’ condition was used for both the forward and rearward directions (see italicized values in Table 2).

The data were tested and confirmed to be multivariate normal with appropriate skewness and kurtosis [61]. The multivariate tests suggest that there are overall statistical differences in tipping angles as a function of the EPW model. Post-hoc analysis results (Table 1, superscripts) showed groupings among the EPWs for each tipping direction, where the groupings (a-d) represent the lowest to the highest tipping angle groups, respectively.

Table 3 Dynamic Stability Scores. Mean (standard deviation) are presented; when the score was equal for all three EPWs for each manufacture, standard deviations are not included. Only sections which were not all identically scored with a ‘4’ are presented. RUH(sta)=rearward stability when starting uphill on a slope; RUH(br)=rearward stability when braking after traveling forward on an uphill slope; RDH(br)=rearward braking stability when traveling backwards down a slope; R-TRAN=rearward stability when traveling down a step transition; F(br) Forward braking stability when traveling forwards; F-TRAN=forward stability when traveling down a step transition; LAT-TRN= Lateral stability when turning on a downhill slope; Lat-TRAN=Lateral stability when one side of the EPW travels down a step transition. * 2 EPWs were unable to climb the inclination. Underlined values indicate that there were significant differences in that section based on the Kruskal-Wallis test ($p<0.05$). Superscripts a, b and c are groupings found by the pair-wise Mann-Whitney U tests, where ‘a’ represents the highest and thus most safe condition.

SECTION	RUH (st)		RUH(br)		RDH(br)		R-TRAN	F(br)			
deg/mm CHAIR	6	10	3	10	6	10	50	0	3	6	10
GOLD	4^a	4^a	4	4^a	4^a	4^a	4*	3	2^b	2	2^b
PRMO	4^a	4^a	2.7 (1.2)	4^a	4^a	4^a	4	1.3 (0.6)	1.7^b (0.6)	1.3 (0.6)	1^c
ELMO	2^b	1^c	4	1^b	2.3^b (0.6)	1^b	3.7 (0.6)	4	4^a	4	4^a
INVA	3.3^a (0.6)	2.3^b (0.6)	4	4^a	2.7^b (0.6)	1^b	4	4	4^a	3.0 (1.7)	1^c

SECTION	F- TRAN		Lat-TRN	Lat-TRAN	
deg/mm CHAIR	25	50	10	25	50
GOLD	4^a	4^a	4^a	4	4
PRMO-1	2^b	2^b	2^b	3.3 (1.2)	3.0 (1.0)
ELMO-1	4^a	3.7^a (0.6)	4^a	4	4
INVA	4^a	4^a	4^a	4	4

Dynamic Stability scores (Table 3) demonstrate the EPWs behavior during maneuvering on sloped surfaces. Scores range from 0 to 4 where a "4" indicates that at least one wheels remains on the test plane; a "3" indicates all uphill wheels lift and then drop back to the test plane without anti-tipper contact; a "2" indicates the same as previous but anti-tippers make contact with the test plane; a "1" indicates all uphill wheels lift and the EPW get stuck on the anti-tippers, and a "0" indicates the EPW tips completely. Potentially dangerous events (e.g., when both wheels lift from the test plane) are indicated by a 3 or below, and are of special concern when they occur on the lower inclinations (such as 0 degrees) such as in section 9.2. Two data points were not recorded because the EPW could not climb the step transition. The Kruskal-Wallis test showed significant differences in all sections (see underlined headings in Table 2) except 8.5, 9.3, 10.4, and 10.5. Significantly different groups found by the pair-wise

Mann-Whitney U tests (shows as superscripts a, b, and c in Table 3) demonstrate similarities and differences among and between manufacturers.

Table 4 Braking Distance mean and (standard deviation) (cm). rel= normal release; rev= joystick reversal; off = controller power off. *Data was not available because the EPW skidded down the slope and never came to a complete stop. The Kruskal-Wallis test suggested overall differences in all conditions except the 10 degree/forward (underlined). Superscripts show significant groupings predicted from the Mann-Whitney U tests, where a is the lowest braking distance, and d the highest (most unsafe) distance.

Inclination	**Horizontal**						**3 Degrees**					
direction	**Forward**			**Reverse**			**Forward**			**Reverse**		
EPW/Brake	**rel**	**rev**	**off**	**rel**	**rev**	**off**	**rel**	**rev**	**off**	**rel**	**rev**	**off**
GOLD	79.3^{d}	72.4^{c}	56.6^{c}	33.4^{b}	26.3^{b}	26.1^{c}	91.9^{d}	79.2^{b}	62.2^{b}	36.2^{b}	28.8^{b}	28.6^{b}
	(6.7)	(4.0)	(4.8)	(4.0)	(5.4)	(4.4)	(6.5)	(2.2)	(3.5)	(3.5)	(2.6)	(3.4)
PRMO	52.7^{c}	36.3^{b}	40.4^{b}	38.0^{b}	30.1^{b}	23.7^{c}	65.2^{c}	44.7^{a}	46.3^{a}	40.8^{b}	32.4^{b}	26.8^{b}
	(1.7)	(2.3)	(6.6)	(2.3)	(1.4)	(1.5)	(3.0)	(5.5)	(8.1)	(3.3)	(2.8)	(0.2)
ELMO	41.2^{a}	30.4^{a}	28.5^{a}	12.4^{a}	7.5^{a}	7.6^{a}	34.3^{a}	34.2^{a}	33.2^{a}	12.8^{a}	9.7^{a}	8.8^{a}
	(1.8)	(2.0)	(2.9)	(1.5)	(0.3)	(0.3)	(16.3)	(4.5)	(7.1)	(1.0)	(2.1)	(1.1)
INVA	45.7^{b}	38.0^{b}	38.4^{b}	13.2^{a}	8.3^{a}	10.3^{b}	45.8^{b}	38.1^{a}	40.9^{a}	13.7^{a}	7.4^{a}	10.4^{a}
	(1.8)	(3.0)	(2.6)	(1.1)	(0.7)	(1.2)	(1.4)	(2.7)	(2.1)	(2.0)	(0.8)	(0.8)
Inclination	**6 Degrees**						**10 Degrees**					
direction	**Forward**			**Reverse**			**Forward**			**Reverse**		
EPW/Brake	**rel**	**rev**	**off**	**Rel**	**rev**	**off**	**rel**	**rev**	**off**	**rel**	**rev**	**Off**
GOLD	88.2^{b}	73.7^{b}	58.7^{b}	40.2^{b}	39.0^{b}	39.9^{c}	91.4	90.6	76.8	*	*	
	(20.5)	(18.2)	(13.9)	(7.9)	(5.8)	(5.8)	(16.1)	(10.3)	(11.5)			*
PRMO	73.4^{b}	58.8^{b}	59.8^{b}	51.9^{c}	47.0^{b}	39.2^{c}	109.3	87.7	117.3	99.8^{c}	91.6^{c}	95.6^{b}
	(2.7)	(8.3)	(12.0)	(1.3)	(5.2)	(1.8)	(26.9)	(17.4)	(9.8)	(20.5)	(13.3)	(32.0)
ELMO	50.7^{a}	40.4^{a}	39.8^{a}	14.8^{a}	10.6^{a}	9.8^{a}	*	*	*	13.3^{a}	7.5^{a}	7.5^{a}
	(5.3)	(7.0)	(7.1)	(2.0)	(0.6)	(0.3)				(0.7)	(1.7)	(1.6)
INVA	50.2^{a}	42.9^{a}	45.6^{b}	15.2^{a}	9.8^{a}	11.6^{b}	49.1	41.3	56.0	14.8^{b}	10.2^{b}	26.4^{a}
	(7.2)	(0.2)	(0.2)	(1.4)	(1.0)	(0.9)	(5.1)	(3.5)	(24.6)	(0.5)	(0.2)	(23.1)

Forward and reverse braking distances on four test planes (0, 3, 6, and 10 degree) for three braking conditions are presented above (Table 4). We performed a Kruskal-Wallis test for overall differences across manufacturer (because the data were not multivariate normal) and found significant differences in all testing conditions except the 10-degree/forward condition (likely because of missing data due to some EPWs skidding down the test plane). Manufacture-wise groupings were calculated with multiple Mann-Whitney U comparisons and are presented as subscripts in the table.

Energy consumption results show the theoretical range of the all EPWs, which are all relatively high (mean Km +/- SD)): GOLD=18.2 (0.83); INVA=17.2 (0.78); ELMO=22.5 (0.73); PRMO=32.0 (0.96). ANOVA results found significant differences across manufacturers, and Tukey's post-hoc results are reported to demonstrated that PRMO had the highest theoretical range, followed by ELMO, followed by GOLD and INVA (not significantly different from each other).

Maximum speeds (Table 5) were significantly different across manufacturers, directions, and angle. The general trend (fastest to slowest EPW) was generally similar across direction and angle, suggesting selected EPWs (e.g., GOLD) have overall higher top speeds.

Table 5: **Average (standard deviation) maximum speed (m/s) in forward and reverse on three test-plane inclinations. Superscripts indicated groupings of speeds for each inclination and direction (a-d from low to high) found with a Tukey's post-hoc test.**

Direction		**Forward**			**Reverse**	
Angle	**0**	**3**	**6**	**0**	**3**	**6**
CHAIR						
GOLD	2.29 (0.12)^{c}	2.10 (0.09)^{c}	1.91 (0.08)^{d}	1.26 (0.07)^{c}	2.34 (0.06)^{c}	2.64 (0.09)^{a}
PRMO	1.79 (0.10)^{b}	1.75 (0.07)^{b}	1.59 (0.03)^{c}	1.04 (0.10)^{b}	1.94 (0.01)^{b}	2.21 (0.01)^{a}
ELMO	1.39 (0.03)^{a}	1.34 (0.05)^{a}	1.13 (0.02)^{a}	0.68 (0.03)^{a}	1.42 (0.02)^{a}	1.59 (0.05)^{a}
INVA	1.43 (0.04)^{a}	1.37 (0.07)^{a}	1.27 (0.05)^{b}	0.62 (0.02)^{a}	1.47 (0.04)^{a}	1.61 (0.07)^{a}

All EPWs passed the climatic testing section without adverse responses. The only noticeable effect of the cold-storage condition was on the front (drive) tires of the PRMO EPWs, which had slight flat-spots after removal from storage. These flat spots were noticeable when maneuvering the EPW, especially at high speeds. After several weeks of testing, the tires became completely round again.

All EPWs passed the static and impact tests of section 8. Fatigue (durability) tests varied between and within manufacturer (Table 6). All but three EPW (two ELMO and one PRMO) did not achieve the required 400,000 equivalent cycles required by the standards. Failure modes included drive-train or seat related failures (GOLD). Seats either bent (1) (Figure 4) or bolts attaching the seat post to the frame broke (2) for the GOLD. No significant differences between or within factor (manufacturer) were found with an ANOVA. Value reported as cycles per dollar was calculated by normalizing the equivalent cycles by the retail price of the EPW. One variation in testing occurred with ELMO-3, which initially failed prematurely on the curb-drop test due to a backrest adjustment problem (at nearly 400,000 eq. cycles). Because we believed this failure was due to a miss-adjusted backrest, we replaced the backrest with the ELMO-2 backrest and continued testing.

Table 6: **Equivalent cycles and failure mode. Bolded values indicate which EPWs passed the ANSI/RESNA requirement of 400,000 equivalent cycles.**

EPW	Eq. Cycles	Value (cycle/$)	Failure Mode
GOLD-1	236510	118.55	Seat
GOLD-2	99863	50.06	Seat
GOLD-3	234950	117.77	Seat
PRMO-1	**425968**	157.53	Drive train
PRMO-2	9759	3.61	Drive train
PRMO-3	136396	50.44	Drive train
ELMO-1	44821	17.23	Drive train
ELMO-2	**417928**	160.68	Drive train
ELMO-3	**824628**	317.04	Drive train
INVA-1	101770	61.57	Drive train
INVA-2	46428	28.09	Drive train
INVA-3	25694	15.54	Drive train

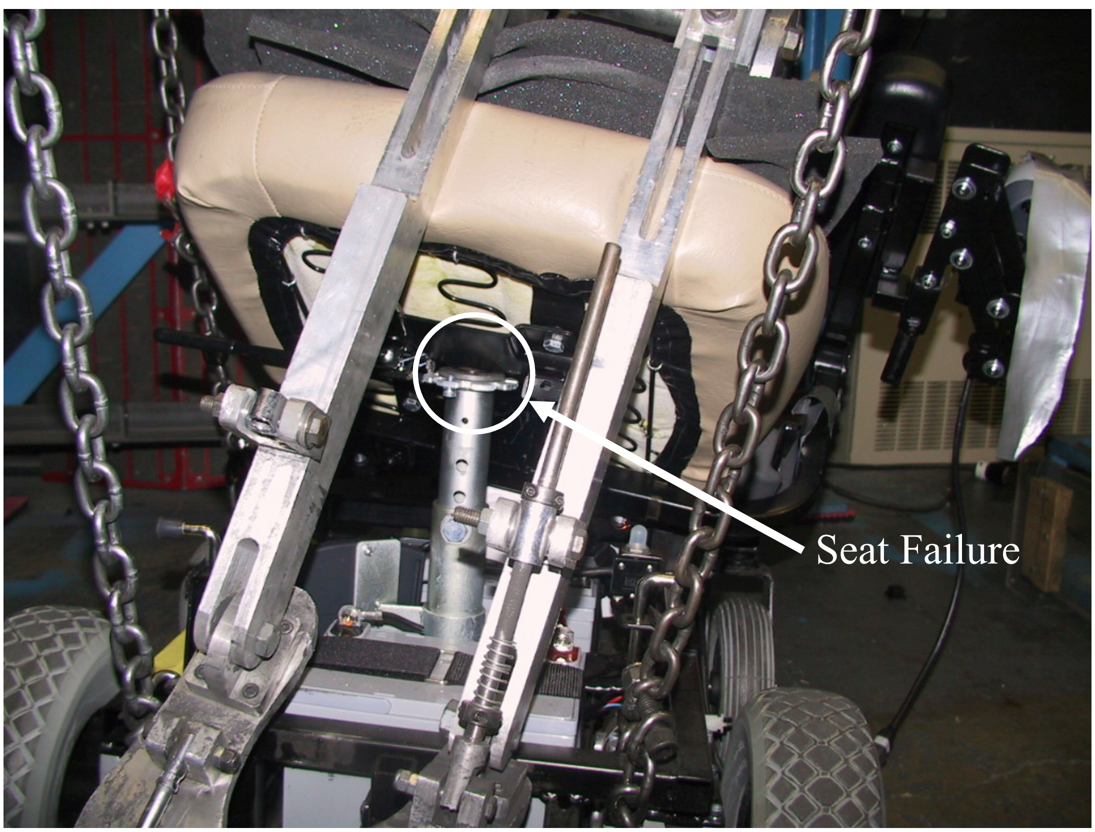

Figure 7 Close-up of bent seat failure on the GOLD during curb-drop testing

The response of the power and control systems varied widely for the EPWs from each manufacturer. Because of the number of tests included in Section 14, we will only report adverse effects:

1) 2 of 3 ELMO EPWs failed the stalled condition testing (6.14), resulting in smoke coming from the motors when the EPW was stalled against a wall with the controller pushed forward.

2) 2 of 3 ELMO EPW battery chargers were damaged when performing the reverse polarity at the battery test (6.10).

3) All GOLD EPWs failed the controller command signal-processing test (6.12) because the joysticks had electrical failures; all joysticks were replaced so testing could continue.

4) All GOLD EPWs failed the reverse-polarity battery charger connection test (9.2.5) suggesting that the current continues to flow from the battery charger even if its polarity is switched.

5) All INVA EPWs failed the charging battery safety test (6.9) which demonstrates that the EPW can be driven while the battery is being charged (i.e. it is plugged into the wall outlet).

3.4 DISCUSSION

Overall, we found significant differences between manufacturers of nearly all variables tested. Static stability varied significantly across manufacturer, and was highly sensitive to the direction the EPW was facing. Thus, an EPW highly stable in the forward direction, may be unstable in the rearward direction (e.g., ELMO), or vice-versa (e.g., PRMO)

(Table 2). Stability in all directions is important as shown by Corfman and colleagues [62] who demonstrated that events can occur both descending and ascending obstacles (ramps and curb-cuts, respectively). Overall, GOLD EPWs were most consistent across directions, but were not the most stable EPW for any of the four directions. During maneuvering and testing, PRMO proved to be the least stable in the forward direction, and care should be taken when setting this EPW up for the user (i.e., unstable seating setups can exacerbate the problem). Note that our analysis used the lower of the stability measures (where more than one was available) by considering the case when the wheels first left the ground, instead of when the anti-tip devices failed. This allowed us to compare the angles where the user would likely lose control of the EPW. These values do not imply the EPW would tip (e.g., the tipping angle for the ELMO in the rearward direction doubles when considering the anti-tip devices). Also, we report the data for the least-stable seat and component setup to be conservative. The static stability of the these low-cost, non-programmable EPWs were comparable to the higher class of EPWs reported by Rentchler and colleagues [56] with the exception of the ELMO, which had a much lower rearward stability tipping angle than any of those reported in the other study.

Significant differences between manufactures varied for dynamic stability scores also. Differences between manufacturers were more pronounced for the higher inclinations (which is consistent with another comparison study of higher class EPWs [55, 56], except for the forward stability when braking (Section 9.2)), which is one of the more important measures (Table 3). As discussed above, the PRMO was noticeably unstable in the forward direction, even on a horizontal test-plane. INVA forward instability was also poor, but this was noticeable only on the 10-degree slope. Results from rearward stability (sections 8.2-8.4) suggest that the ELMO and INVA are unstable at higher test-plane inclinations. Note that no EPWs scored a zero, indicating that none completely tipped over. Both dynamic and static stability measures are important when choosing an EPW, since tips and falls account for the majority of injuries of wheelchair users[54].

Braking distances were significantly different across manufactures (Table 4), but groupings were largely consistent across directions (forward/reverse) and test-plane inclination. Overall, GOLD and PRMO were the fastest of the EPWs, and ELMO and INVA were the slowest. Without programmability of the controllers, braking distances are not in the control of the clinician who sets up the EPW. Thus, the reported braking distances are important to be aware of for clinicians who have concern regarding the user's ability to control the EPW, especially when stopping. Of the EPWs we tested, braking distances are much lower, in general, than those of the higher-class EPWs reported in the literature[56]. But because the higher class EPW braking distances are reported by testing the EPW with the controller programmed for maximum velocity, this comparison is not entirely valid (since they can be programmed to restrict maximum velocity).

Energy consumptions results demonstrated a significant difference across manufacturers, but all theoretical ranges were relatively high. In a study investigating the driving distances of EPW users, researchers found that subjects traveled a mean (+/- SD) of 8.35 (7.07) Km over a five day period [63]. This average increased by over two-fold (17.16 (+/- 8.7)) when users were participating at a sporting event, but still fall below the theoretical range of the EPWs tested in this study. Thus, our results suggest that on average, all tested EPWs would reliably run for more than five days of use without recharging (which is typically done daily [63]). This finding should be qualified since the test evaluates energy capacity under idealized conditions (horizontal test-plane, near constant amp draw), it does not take into consideration that batteries lose their charge capacity over time, and it does not include the energy consumptions due to starts/stops.

Maximum speeds varied across manufacturer, direction and test-plane angle, but there were consistent trends for each condition (i.e., the fastest and slowest EPWs were similar for all conditions) (Table 5). In this study, we present the maximum speeds because it can be an important safety issue since the non-programmability of the controller implies the clinician setting up the EPW does not have control over the maximum speed of the EPW. Thus, a user who may not be able to safely maneuver the EPW at high speeds could raise the manual speed adjustment (on located on the joystick for all EPWs tested) and injure themselves. While it is expected that braking distances will be longer for the faster chairs (which was true, in general: Table 4 & Table 5), we believe it is more informative with the low-cost non-programmable EPWs to present the speed and braking distances separately (even though braking distance comparisons typically control for maximum speeds [56].

All EPWs successfully passed climatic testing, which was an improvement over a previous study [56] of higher grade EPWs . We noticed only that the PRMO had a flat spot on the tires, presumably because some of the airless insert material lost its elasticity during the freezing portion of the tests. While the tires did recover their shape after several weeks, manufacturers should be careful to use the appropriate material that will not change properties during storage or shipping.

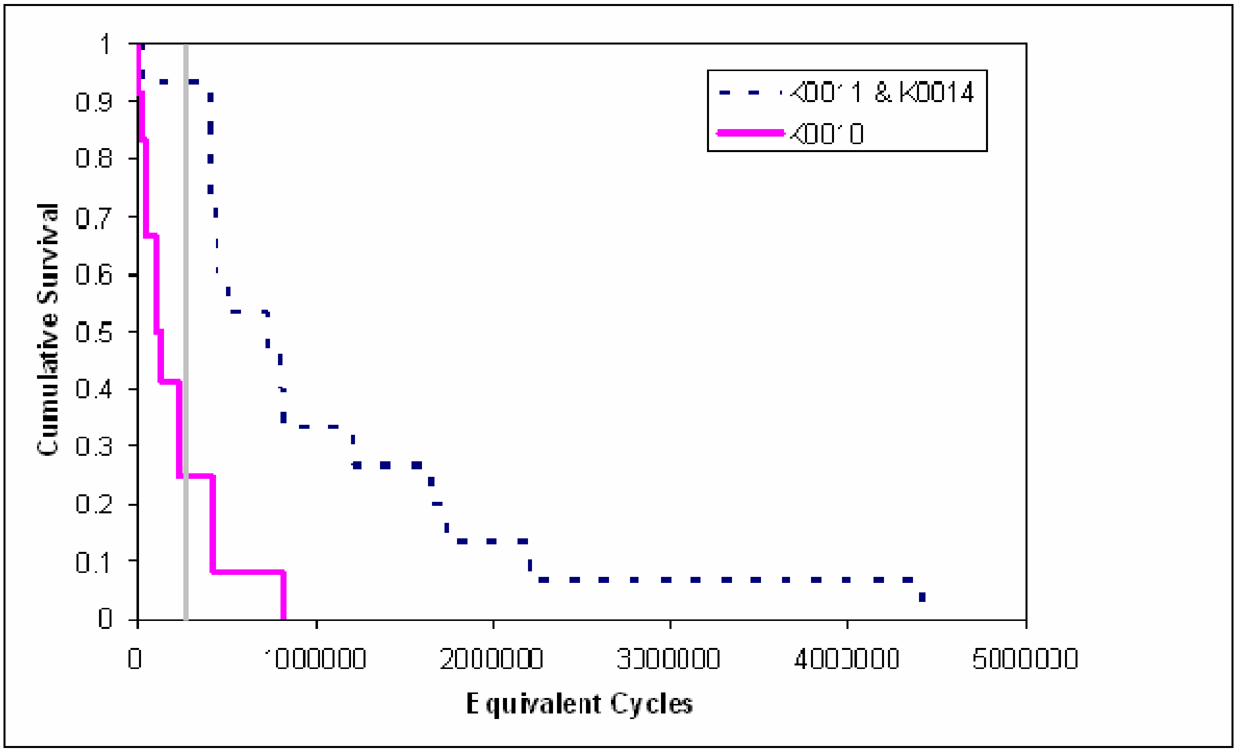

Figure 8 Survival curve comparing rates of K10 to those of the higher classified EPWs. Survival of the low-cost EPWs we tested at the 400,000 equivalent cycle mark (vertical gray line) is 25 vs. the 0.8 survival of the other EPWs.

Section 8 results (Static, Impact and Fatigue Testing) were overall good for the static and impact tests, and poor for the fatigue tests (Table 6). The fact that only 3 of the 12 (25%) EPWs tested successfully completed 400,000 equivalent cycles show the distinct difference between the low-cost EPWs we tested and the higher-cost EPWs which had a success rate of 13 of 15 (86.7%) [56] (Figure 8). The majority of failures were drive-train (motor or gearbox) failures, but the GOLD consistently failed due to seat failures. All types of failures pose a concern since they may lead to injury of the users [54]. While rate of failures were higher for our EPWs, the low cost of the EPW resulted in relatively high values (cycles/$) for these EPWs. Value ranges spanned from 3.6 – 317 cycles/$ for the EPWs tested here and from 27 – 196 cycles/$ for the higher classified EPWs [55]. These results suggest high variability in value, and also imply that overall, the low-cost non-programmable EPWs provide more value to the user. The consequence of this low-durability but high value could be two-fold: either insurance companies would not provide a replacement EPW within the 3-5 years (the life cycle expected for an EPW); or the insurance company would purchase replacements, requiring the typical paperwork and processing time, which would inflate the price (and thus, lower the value) of these EPWs for the user and the insurance company. Furthermore, the wide variability of the equivalent cycles before failure within manufacturers suggests that estimates on the life of any of these EPWs is not reliable, and may harm the user (because it may strand the user) which would negate the cost-benefits of using these lower quality EPW. Clearly, our results demonstrate that the quality of the EPWs we tested need to be improved so the user can have more reliable mobility. An important concern is that manufacturers may use the basic design of the low-cost, non-programmable EPWs we tested and upgrade only necessary portions to fit within the proposed Medicare coding system [60], in order to compete in the competitive bidding for durable medical equipment that Medicare intends to begin[59].

Power and control system testing (Section 14) demonstrated some serious safety concerns for all but the PRMO EPWs. Of particular concern was the failure of the two ELMOs during the stalled condition testing (which simulates a user driving against an obstacle and not releasing the joystick). In practice, this behavior could have happened by accident (e.g., a user is for some reason unable to release the joystick when they stall) or intentionally if a user attempts to user their EPW to negotiate an obstacle. In this situation, a resetting circuit-breaker (automatic or manual) is supposed to trip in order to stop current flow to the drive system. With two of the ELMOs this breaker failed to trip and caused the motors to heat to the point where smoke came out of them. If the EPW was stalled for longer then the 2 minutes the test required, it may have caught fire. Another potentially hazardous behavior we found was with the INVA during charging. Because the EPW can be maneuvered while being charged, if a user does not unplug the EPW it they may pull the cord out of the wall or the EPW, causing them or others harm. Other adverse behaviors during this testing were related to wiring short-circuits. This can occur at several places on the EPW due to wear and tear, or user or technician error. The results of these tests caused failures of the battery chargers (ELMO) and controllers (GOLD).

Our results provide additional evidence that EPWs (and wheelchairs in general) on the market still do not meet the recommended standards when tested independently. As our results show, all the low-cost, non-programmable EPWs we tested have low durability overall and thus are not likely to last the expected 3-5 years of use. Results from the power and control system, stability (static and dynamic), breaking distance, and maximum speed varied across manufactures. This data will assist clinicians to identify the best EPW for their client.

While we followed the ANSI/RESNA standards testing methods explicitly, this study, by no means, describes the behavior of all low-cost non-programmable EPWs overall. We made an effort to minimize bias by randomizing testing order, and chose a selection of low-cost, non-programmable EPWs that represented the largest manufacturers of these wheelchairs. Because of the expense, and the time required for testing, we were unable to test more than three wheelchairs of the same model and manufacturer. The US FDA typically requires testing results for one to three identical devices for certification, which is what we based our sample size on, given the high cost of these devices. Although using a test-dummy can reduce variability in the results, it is only an approximation of an average user. Results from other manufacturers may show different results from what is presented here. The overarching result from this study is that outcomes of the different tests were not consistent *between* manufacturers, and in some cases (as with durability), *within* manufacturers. Thus, we feel that we have demonstrated the wide range of behaviors that are represented by this class of EPW.

One informative evaluation that we did not perform, was to test the affect of programmability vs. non-programmability. In the clinic, our experience is that programmability is nearly always used, since it allows the EPWs to be fitted to a user's abilities and their environment; the users' abilities, adaptive strategies, and environments vary widely, suggesting that no one program would be appropriate for all EPW users. This experience, though, is clinical, and does not objectively test the importance of programmability for user maneuverability or safety. The ANSI/RESNA standards do not include such a test, even though it may help convey the importance of the programmability. Furthermore, the value of device comparison studies is maximized when the devices tested are new on the market, and durability and safety issues are not known. Future studies should look at these new devices, such as the new pushrim-activated power-assist wheelchairs, and the high-strength ultra-light weight manual wheelchairs that are widely prescribed.

3.5 CONCLUSION

We found large variation in the test results from the EPWs that we tested, raising concern for users' safety and the long-term durability of these devices. Clinicians and current and future users of these devices should be aware of these shortcomings to avoid injury. In the current flux of the durable medical equipment (DME) industry, from Medicare coding changes to competitive bidding contracts, there is concern that quality of the DME will decline in order to lower costs. Our results show that simply using the low-cost, non-programmable EPWs as a base for higher classified EPWs that fit Medicare's coding systems would be a mistake, and engineering changes must be made to the current models before they will reliably and safely provide mobility.

3.6 ACKNOWLEDGEMENTS

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4.0 DESIGNING ASSISTIVE TECHNOLOGY FOR LESS-RESOURCED ENVIRONMENTS: AN ONLINE METHOD TO GAUGE ACCESSIBILITY BARRIERS AND COLLECT DESIGN ADVICE[1]

4.1 INTRODUCTION

Designing assistive technology (AT) for developing countries is a difficult task, especially for designers who are not familiar with the target region. When poor devices are designed or transferred from other regions, they can fail rapidly, and require a complete redesign of the technology. This can be time-consuming and costly, especially if the poorly designed devices are widespread. This is the scenario which has occurred for both prosthetic limbs [29], and for manual wheelchairs [3].

The widespread transfer of the solid ankle cushioned heel (SACH) prosthetic foot was quickly rejected when it was introduced in India. Within a society where squatting is common while doing many daily tasks, the inflexible SACH foot was nearly unusable and was consequently abandoned [29]. The solution to the problem was through the local resources of a doctor, who developed the Jaipur Foot [29], which is aesthetically and functionally similar to the

[1] For submission to the International Journal of Rehabilitation Research Coauthors: Jefferds, Cooper, Chhabra, Nagai

intact foot, and can be produced locally for costs that are affordable to the high and middle wage earners, and are covered by the social-welfare system for the low wage earners.

A similar scenario is occurring with the widespread transfer of inappropriate hospital-style wheelchairs to developing countries. According to anecdotal and scientific evidence, these devices fail rapidly [10, 11, 13, 15, 19, 29, 44, 53], leaving the user without independent mobility, and the purchaser (who is often different than the user) with a sense of wasted opportunity and money.

Two organizations have been leading the effort to improve the quality and appropriateness of manual wheelchair technology in these countries using different design approaches. Whirlwind Wheelchair International (San Francisco, CA, USA), uses an open-source design approach, where product designers collaborate with wheelchair builders worldwide to improve and adapt their manual wheelchair design for developing countries. While the designs which have evolved from this approach are high in quality, it has taken many years to build the network of wheelchair builders who can provide valuable feedback about the design. Motivation Charitable Trust (Bristol, UK) uses product designers at its headquarters and in the field to help design their wheelchairs for low-income countries (as well as service deliver programs and training methods). Over a span of 15 years, Motivation has successfully developed high-quality wheelchairs for local, small-scale manufacture, as well as medium-to-large scale imported products.

Unfortunately, the hospital style wheelchairs have the competitive edge over the better-designed and built wheelchairs from Whirlwind and Motivation. Because hospital wheelchairs are ubiquitous and low-cost (in many cases donated), to the uninformed user or charitable foundation, they are the obvious choice. And because potential wheelchair users are rarely educated about the differnent choices of wheelchiars, they are powerless to demand higher quality devices that are more appropriate for their enviornment. Thus, because low-cost generic wheelchairs are already so prevalent, the battle to improve their technical quality is more one of education and policies (against poor quality devices) than it is of technical prowess.

Because history often repeats itself, the same costly and time consuming scenario that occurred with the transfer of inappropriate prosthetic limbs and manual wheelchairs is likely to occur with other types of AT: a cycle of 'redesign' and 're-education' will need to occur, at the cost of the end-users and donors. To help avoid these high costs and inefficiencies, designers must insure the AT is appropriate for the target region *before* it is transferred. For product designers in developed countries (where they are most numerous), the distant locations and unfamiliar environments of developed countries make this task difficult.

Only one AT comprehensive product design project for developing countries has been described in the literature. Mulholland and colleagues [31-33] performed a comprehensive design project of a mobility device for women in India. A needs assessment was performed in India [33], as well as many design reviews and iterations in their home country of Canada with experts familiar with the Indian environment [31]. Finally, focus groups were performed in India with several of the women who had participated in the initial needs assessment [32]. The design process described in these series of papers is a classic design approach, but in this case done at a distance requiring several visits to India.

While Mulholland used a respected, successful product-design approach, implementing the approach can prove costly and time-consuming. If alternate design tools were available or developed which would speed and/or lower the cost of the design process, more designers may take on these challenging projects. This is especially important as the pool of engineering students who are interested in social causes grows—as evidenced by the recently created student groups such as Engineers for a Sustainable World and Engineers without Borders.

As part of a larger project with Indian researchers and AT manufacturers, our laboratories are designing an electric powered wheelchiar (EPW) to meet the growing demand for AT in India. Few EPWs are currently available in India, so a prescedent of low-quality inappropriate devices have not yet been set and thus does not have to be 'undone.' But there is a slow increase in the availability of these devices—both from domestic and international sources. Ottobock and Invacare both provide EPWs in India, but the costs are prohibitive (220,000 rupees, or approximately $5,000 US Dollars), and limit sales to only those with mid to high income. From casual discussions with Otto Bock sales representatives, they sell less than 10 units per month in India. Importers and domestic manufacturers (of which there are 3-5) import or manufacture low-cost and low-quality EPWs that typically have no suspension. While sales figures are still small (likely less than 50/month total based on conversations with local manufacturers and importers), and awareness grows of powered mobility, there is a risk that these inappropriate devices will become widespread in India (and other developing countries). Thus, the window of opportunity to design an appropriate EPW for India is closing; soon, low-quality devices may dominate the market

Faced with limited funding, and the daunting task of perfoming a needs assessment in a country as large and diverse as India, we looked for low-cost and effective approaches to understanding the living and working environments of wheelchair users in India. Needs assessments commonly employ the tools of ethnographers, who study the behavior of people [64, 65]. In some cases this includes field studies to monitor individuals, and often can use video or film photography to capture key behavoirs or situations for further analysis, or as a way to present information about the subjects at a future date [65]. While these may be the most appropriate tools for needs assessment, in their classic form a signficant human, financial, and time investment is required for a comprehensive field analysis. Additionally, the outcomes of these studies are inherently qualitative, resulting in relatively subjective results that depend on the researcher(s) reviewing the field data.

Borrowing from the tools of ethnographers and social scientists, we used photographs as our main source of information about the Indian terrain and the lives of wheelchair users in India. Rather then relying on gathering open-ended qualitative data, and trying to interpret it accurately, we devised a method to have experts world-wide answer well-directed questions about the photos, and respond with both qaulitative and quantitative information.

For this needs assessment, we were specifically interested in the questions of which barriers to accessibility were most *severe* and *prevalent* in India so that the EPW could be specifically tailored to manuever in the homes and communities there. We were also interesetd in the possible design features and home modifiations that experts could suggest so that an EPW could be effective for users in India.

4.2 METHODS

4.2.1 Phase I-Camera Distribution and Collection

In spring, 2005, the Indian Spinal Injuries Center (ISIC) in New Delhi, India, recruited a convenience sample of 50 wheelchair users to participate in an Institutional Review Board approved camera study. After informed consent was provided, demographic data were recorded (age, gender, disability, occupation, financial background, and rural/urban setting) and subjects were given a disposable camera (28 exposures) with self-addressed envelopes and a small amount of money to cover shipping ($3.00). Directions were given to the subject in person and on a form, instructing them to take photos of the accessibility barriers they encountered in and around their home and work, and in their community. Friends and/or family members were also encouraged to take photos of the subject maneuvering through these barriers. The subjects[2] were also instructed to write down brief descriptions of each photo on the back of the lined instruction sheet.

After the cameras were returned to the ISIC, they were developed directly to digital images, transferred to the Human Engineering Research Laboratories (HERL) under an exempt IRB approved by the University of Pittsburgh, de-identified, and screened. Photos that were unclear (because of poor focus or lighting) were removed from the dataset, and two wheelchair users at HERL (not of Indian descent) were asked independently to screen the de-identified photos. Screeners were asked to view all of the photos in the dataset that did not have text descriptions (provided by the photographers), and mark which ones did not display any accessibility barriers. Photos that were marked by both screeners were discarded and not included in the final dataset.

[2] For the remainder of this chapter, subjects in phase I will be referred to as ‘photographers’ to distinguish them from phase II subjects.

4.2.2 Development of an Online Survey System

4.2.2.1 Back-End Architecture

The online survey was developed on a personal Windows computer running the web server Apache 1.3 [66] and transferred to an IIS 4 server after development. The interface was written using the Hypertext Preprocessor (PHP) [67] which interfaces with a database stored on the web server. A My Server Query Language (MySQL) [68] database was used to maintain data, and communication between the interface (PHP) and the database was achieved through ADOdb [69] a database abstraction scheme. We used ADOBD to preserve the possibility of using other databases (e.g., Access) without major modifications to the PHP code.

4.2.2.2 User Interface

A subject interested in the study views an introduction page, which explains the purpose of the study and a presents a model of the questionnaire page. Following the introduction, the subject navigates to a registration page, which records non-identifiable demographic information such as gender, age, country, disability (if any), employment status; and familiarity with power wheelchairs and accessibility issues in developing countries. Finally, the subject is asked to enter a unique username and password combination so they can revisit the site and continue the questionnaire at a convenient time. When the user submits the registration, the information is stored in the database, and a subject-specific random sequence of images is generated.

Upon logging in with their username and password, the subject is presented with the first of their 50-image sequence, a 13-question survey with a series of bullets blow each question. Also, two text boxes are presented to record open-ended feedback from the subject. As the subject progresses through each photo, the survey bullets and the text boxes refresh so that each photo allows for a new set of responses. Figure 9 shows an annotated screen capture of the user interface (which also is used as the 'help' page for the subject).

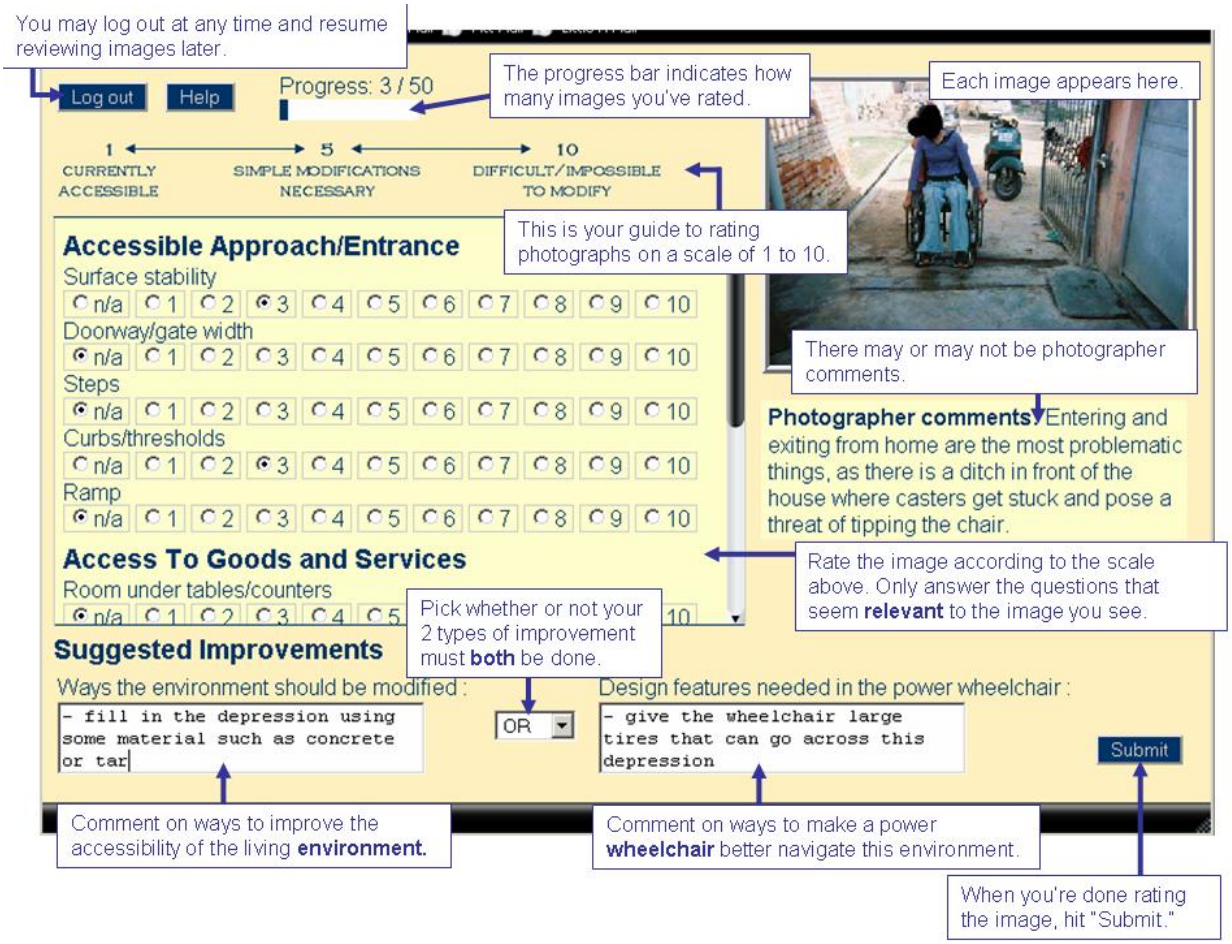

Figure 9 An annotated screen capture of the user interface for the online survey. This is also used as a 'help page' that the subject can access at any point during the survey.

The user rates accessibility issues on a scale of 1 to 10, where 1 indicates "completely accessible", 10 indicates "completely inaccessible", and a 5 indicates that the environment could be made accessible with reasonable modifications such as the addition of a ramp. The questions were drawn from the American Disabilities Act Accessibility Checklist [70], covering issues of steps, rough terrain, doorway widths, and ramps, etc.

The user is instructed not to answer every question, but rather to choose and rate the accessibility features that are portrayed in the photo shown (un-rated questions remain on a N/A bullet). For example, an image of a flight of stairs might merit a response to the “Steps” question only. After the subject completes the rating and open-ended feedback for a photo, they click the ‘submit’ button, and the next image in their subject-specific sequence is displayed. This process continues until the user stops filling in the survey, or completes their 50 photos. When the first set of 50 photos has been rated, the subject is allowed (and encouraged) to rate additional photos, which are presented in sets of 10 randomly selected photos from the dataset.

4.2.2.3 Image Randomization

Because the rating the full set of photos is too time-consuming for anyone using the online survey, we determined through initial testing of the interface that a subset of 50 photos is a reasonable quantity. To ensure website users were shown an unbiased selection of photos, a unique random sample of 50 images were drawn from the dataset for each subject. Furthermore, since some sets of images from each photographer varied in size, we developed a randomization approach that would not be biased toward selecting images from the photographers with larger sets of data. To accomplish this, the randomization scheme proceeded in two steps—first, a random sample from the photographer ID was selected, followed by a random selection of an image from within that photographer’s set of images. Once an image was selected in the random sequence, it was prevented from being chosen again by the randomization scheme (“selection without replacement”*).* The randomization scheme continues to choose in this manner until it had selected a subset of 47 images (3 images are repeated, as described below).

4.2.2.4 Reliability

To test *intra*-rater reliability, the first three images in each sequence were copied and spliced into the 50-image sequence at image number 15, 30, and 45, respectively. Thus, the user sees (and rates) three images twice. Repeated images are mirrored horizontally so that the content of the image remains the same but it is less recognizable.

4.2.3 Questionnaire Refinement

Two rounds of refinement were performed on the user interface. After the first draft of the introduction page and questionnaire were completed, feedback was solicited from five individuals about the interface. Feedback was specifically requested regarding the registration process, the appearance of the application, and any usability problems encountered. During the second round of refinement, two users completed the entire sequence and gave thoughtful answers as if they were truly participating in the study.

4.2.4 Phase II- Expert Analysis

Analysis of the photos using the online survey system was collected under a University of Pittsburgh exempt IRB. Subjects were recruited who were knowledgeable about wheelchair use and design, and accessibility issues: wheelchair users and their family members, rehabilitation engineers, service providers (e.g., physical and occupational therapists), and architects who have experience in design and/or modification of environments to make them accessible.

Subjects registered by completing a short questionnaire which collection information on their demographic, vocation/occupation, and wheelchair-related expertise. Each image is presented with an interactive survey (Figure 1) with questions based on the Americans With Disabilities Act Accessibility Checklist [70].

4.2.5 Statistical Analysis

Subject demographics from Phases I and II, and the survey results, which highlight the severity and frequency of the accessibility issues, were analyzed with descriptive statistics in SPSS v14.0 (SPSS Inc., Chicago, IL). To develop unique groupings of the survey results based on the severity and frequency that the issues were selected, we performed a k-means cluster analysis in Matlab r2006 (Mathworks Inc., Natick, MA); we empirically chose to define 3 unique clusters. The test-retest reliability of the questionnaire was calculated using a correlation coefficient. Additionally, we performed a paired t-test ($\alpha = 0.05$) to determine whether the repeated responses on identical images where significantly different. Open-ended survey results were categorized by keywords and the instances of each of the keywords were counted.

4.3 RESULTS

<u>Phase I</u>: We received 30 cameras with a total of 650 photos from the ISIC. After screening was completed, approximately 500 were found to have viable data that displayed accessibility data (e.g., Figure 2). Individuals who returned the cameras included 20 males and 10 females, were 38 (+/-21) years of age, and live in rural (n=13) and urban (n=17) environments.

User Interface Refinement

Based on the first round of refinement, we reduced the number of images we requested each user to view from 100 to 50. During the second phase of refinement, we received feedback that the questionnaire could become tiring and confusing due to vague images. Also, it was indicated that repeated images (used to test intra-rater reliability) were noticeable. To address the vagueness of the photos, we had two wheelchair users screen the less obvious photos (as described in the methods section), which reduced the dataset by approximately 50. Additionally, to mask the repeated images, we mirrored them horizontally.

Phase II: A total of 72 subjects enrolled in the online study. The registration collected information on several aspects of the subject's disabilities, vocation, awareness of EPW design, and awareness of less-resourced environments (Table 7).

Table 7. Demographic and background information of the online survey subjects

Parameter	Value	Notes
Users	72	Number
Age	43.6 +/- 13.1 (22-73)	Mean +/- SD, (range)
Gender	40/32	Female/Male
Disability	54	Subjects who either have a disability, or have a family member with a disability
Countries	Austria, Brazil, Canada, India, Philippines, South Africa, USA, United Kingdom	Countries Represented
Familiarity w/EPWs	3.2 +/- 0.9 (1-5)	Mean ± SD based on a range indicating no knowledge (1) to expert knowledge (5) of current EPWs;
Awareness of Developing Countries	50	# of subjects reporting familiarity with conditions in developing countries
WC Users	49	# of subjects reporting EPW/Scooter/MWC use (some use multiple devices)
Home Modifications	49	# of subjects reporting home modifications

Subjects on average reviewed 32% of the 50 photos presented; nineteen completed the entire series, and 3 reviewed additional photos. Nineteen completed the entire series and 3 reviewed additional photos. The correlation coefficient of the survey results from repeated images was 0.74, and the null hypothesis-- that the repeated trials yielded the same results--could not be rejected based on the results of two-tailed paired t-test (p=0.712).

The percentage of overall responses (1981) was distributed across the 13 questions with 28% related to surface stability (rough terrain, etc.) (Figure 10, red/oblique hatch). Similarly, subjects rated the severity of the obstacles differently, with 'steps' being the most severe (Figure 10, blue/vertical hatch). K-means clustering was used to define three groupings among the responses, which fall naturally into those with high severity and high percentage, high severity and low percentage, and those with only marginal severity and percentage (Figure 10, horizontal lines above bar graph).

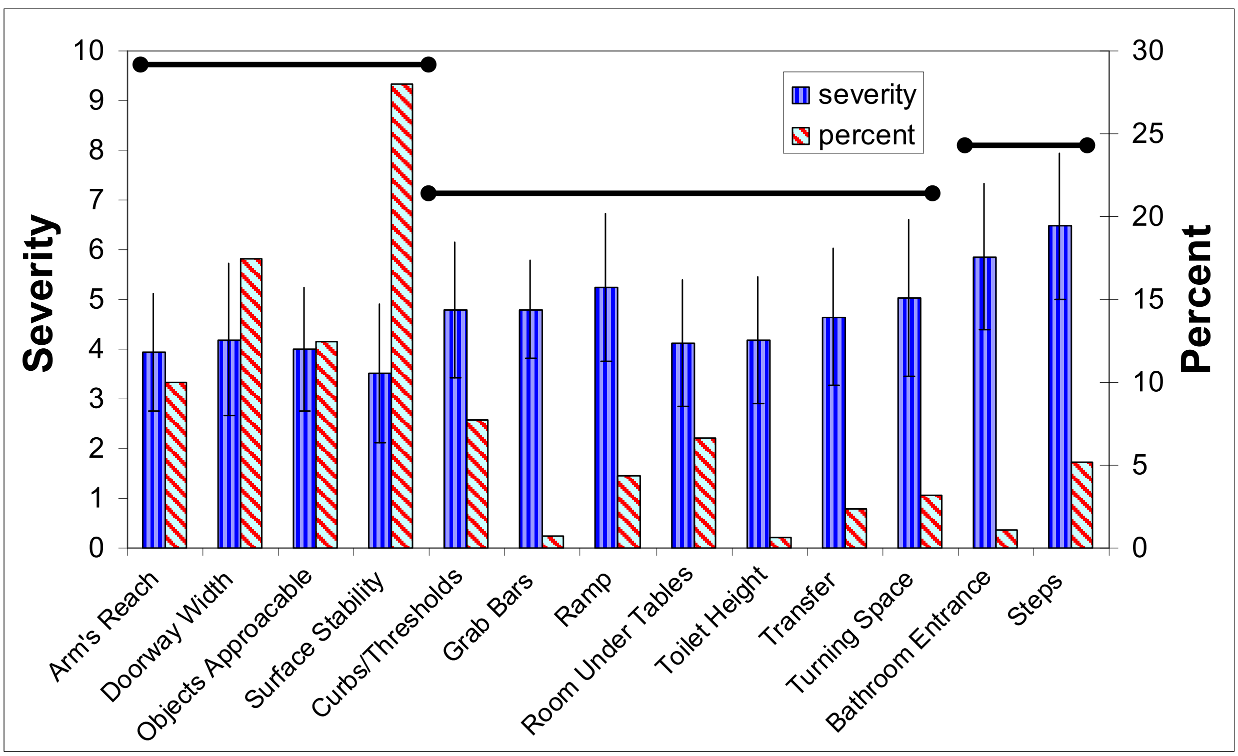

Figure 10 Subject responses to image rating. Average severity (blue, vertical hatch) includes standard deviation error-bars. Percentage of total responses (1981) allocated to each accessibility issue (red, oblique hatch). Bars were grouped by k-mean cluster analysis into three groups, as indicated by the horizontal lines above bars in the graph.

We received over 320 comments related to the wheelchair design, and 570 comments related to home modification, and categorized them by keywords. Selected comments, as well as the number of instances of each of the keywords are presented below (Table 8).

Table 8. Instances of keywords in open-ended feedback of survey; Selected comments are also included to give an idea of the design and home modification advice.

EPW Design Comments		Home Modification Comments	
Keywords	**Instances**	**Keywords**	**Instances**
Seat, headrest, armrest, footrest	50	ground, terrain	14
wheel, tire, caster	136	ramp	147
frame, structure	0	railing, handrail	3
Suspension, shocks, springs	28	door	140
size, width, length, wide, long	42	width, size	16
joystick, controller, user interface	4	toilet, sink, bathroom	25
		bed, dresser, shelf, shelves	41
Representative Comments		**Representative Comments**	
Minimize overall width of power wheelchair.		Fill in all ditches with pebbles or concrete	
Maintain ability for this close diagonal approach and low seat height		Try mounting shelves to wall above knee height in order to use space for turning. Move chairs from under table in order to use space for turning.	
Easy transfer from chair to walker, use of chair while wearing braces		The door hinges could be switched to have the door swing outwards allowing more turning room in the bathroom	
Removable seat, or recline to lower the overall height of the wheelchair. Accessible tie-down points.		Add a stable ramp so the individual can drive up to the gate. The gate should swing away from the ramp (into the picture).	
Able to climb at least 4 inches; able to travel over dirt and rocky surfaces independently		The door must be installed outward and the doorway must be widened. The grab bars and accessible door-knob are needed.	
Foam-filled tires to avoid punctures in case any sharp debris is in yard or on road. The wheelchair would also need footrests so that the feet are not drug underneath the chair on bumpy roads. Trust me, it happens!		Plant turf which stabilizes soil with dense roots without deep leaves/stalks, put down wood chips, pave	
Power chair should have wide rear wheels with deep treads, wide caster wheels, suspension, and tilt system. Should be able to climb to inch to 4-inch curbs.		Relocation of sink to allow for foot rests. Lowering sink height.	

4.4 DISCUSSION

Our goal was to perform a needs assessment of wheelchair users in India and gather design ideas for the development of an EPW. Performing a typical field-study (e.g., [33]) to collect this data would have been prohibitively costly and time consuming giving the diversity and expanse of the Indian Subcontinent. By drawing from the tools used in ethnographic studies [64, 65], and developing an online survey where a wide pool of experts analyzes the subject, we were able to execute a low-cost and effective study to identify, rate, and categorize the types of barriers to accessibility in India. Furthermore, we were able to record several hundred EPW design ideas from experts, providing valuable design ideas to work from during prototype development and modification. The supply costs of the study were approximately $500.00, which included the disposable cameras, shipping expenses to cover the cost of returning the exposed camera to ISIC and the film development costs. Personnel costs were limited to one researcher in India distributing the cameras, and two researchers in the US—the principal investigator and an undergraduate student intern who developed the web-based survey. Now that the website programming has been completed, repeating or expanding the current study can be performed with less time or financial investment apart from internet server expenditures (bandwidth and maintenance).

Disposable camera distribution was successful in part due to the large inpatient population at ISIC. As patients were being discharged, they were asked to participate in the study and the instructions and cameras were distributed to them as well as a small amount of money ($3.00) to cover shipping costs. The relative percentage of men and women with locomotor disabilities in India is 62% and 38% [9], respectively, which is close to the breakdown in our study (67%, and 33%). The vast majority of individuals with locomotor disabilities live in the rural environments (75%) [9], whereas only 43% of our photographers lived in rural environments. Of the total photographers recruited, 56% lived in the rural environment, but because the dropout rate among those living in rural environments was much higher than the urban dwellers (43% versus 18%) our final urban/rural breakdown did not mirror the breakdown in India. We believe that the difficulty of following up with the photographer (via phone or mail) and/or the difficulty of locating a post office in rural environments may have contributed to these skewed dropout rates. In the future, we will anticipate the higher drop-out rate and preferentially recruit individuals from rural environments to achieve a more representative sample.

Only 30 exposed cameras of the 50 distributed cameras (60%) were returned to ISIC. We had hoped to achieve a lower overall dropout rate, but following up to remind subjects is difficult once they are discharged, since many do not have phones or mailing addresses. We had hoped to provide self-addressed pre-paid envelopes to the photographers, but due to difficulty with the Indian mailing system, it was not possible to pre-pay for shipping. Instead, we provided the photographers with 150 Indian Rupees ($3.00), and suspect some may have used the money for other goods or services. Only 1/3 (10 of the 30) of the cameras received included written descriptions of the photos, all of which were displayed below the appropriate image in the online survey. Because there were so many images without descriptions, the interpretation of the important parts of the image was left up to the Phase II subject. In their final comments (collected in the log-off screen), many of the phase II subjects mentioned that they were confused as to what to identify in the photos, which we suspect led the phase II subjects to rate an average of only 33% of the 50 photos in their series. During the user refinement phase of the survey development, we received feedback that the survey may be too long and not give enough guidance on what to rate in the images. We screened the images for content and reduced the target number of images from 100 to 50 in the refinement stage. We also considered adding specific guidance to subjects on what aspects of each image they should rate for the images without text descriptions. We decided not to give that guidance specifically because it would bias the photo ratings to those items the researchers identified as important in the images, which was contrary to the goal of the study to have the experts guide the researchers. In future studies of this type, we will make more of an effort to receive text descriptions of the images directly from the photographers. We may also instruct the photographers to point to the accessibility barrier they are highlighting in the photo with their hand or a specific pointer we provide.

Using the ADA accessibility checklist [70] as the basis for our survey, experts identified a wide range of accessibility barriers in photographs of Indian wheelchair users' homes and communities (Figure 10). While severity of accessibility barriers in different countries may be similar (e.g., steps are severe in all environments) the frequency of each barrier, we assume, differs significantly. For instance, we assume surface stability would not be the most frequent barrier in and around the homes of wheelchair users in urban United States or Europe. In addition to design ideas provided by the subjects participating in the online questionnaire, the frequency of the accessibility barriers can be important information to consider when designing AT for developing countries—the most widely appropriate device would be able to accommodate the most prevalent accessibility barriers. While some of the rating results (Figure 10) were expected (e.g., high frequency of rough terrain) we were surprised to see the low frequency of steps and stairs (5.2% of the responses), given that accessible buildings and homes are not prevalent or mandated in India. Based on our results, we assume that wheelchair users preferentially chose houses and community paths that do not have steps, and thus they did not appear to be a major issue for the photographers.

The severity and frequency results provide insight into the accessibility issues that wheelchair users face in India. To put these results to use when designing a mobility device, it is useful to distill the data so that design criteria can be developed and prioritized based on the severity and frequency of the accessibility barriers. In general terms, if a design addresses the mobility barriers that are most frequent, we assume that design is more widely appropriate for users in India. Additionally, we assumed the *severity* of an accessibility barrier indicated how challenging it would be to design an EPW to overcome that barrier. Thus, designing an EPW which can navigate a frequent *and* severe accessibility barrier may be a difficult design challenge, but it would significantly increase the number of users who can benefit from the device.

To prioritize the accessibility barriers, we used k-means clustering [61] to categorize the severity and prevalence data into three unique groupings (Figure 10, horizontal lines). The first group contains highly frequent, but relatively innocuous accessibility barriers. Overcoming these barriers should not be a significant design challenge, and would result in a more widely useful EPW. The second grouping includes accessibility barriers rated as moderately severe *and* moderately prevalent; this group may contain the most important and challenging accessibility issue to address in the EPW design. The third group includes barriers rated with high severity but low prevalence. Given their rare occurrence, an EPW design may not need to address these issues, but they should be discussed with any potential EPW user during the service provision process.

The correlation between test-retest ratings was relatively high (0.74) and we did not find a significant difference between the repeated ratings. The most common method to gauge reliability is with a interclass correlation coefficient (ICC) [71]; In our case, since each subject did not rate an identical set of photos, calculating a between-subjects error rate would not have been appropriate. In the future, we may have all subjects review a few of the same photos so a more broad error rating can be calculated with the ICC.

It is encouraging that we recorded so many open-ended suggestions for the EPW design features and home modifications. At the current stage of research, we have categorized these responses using keywords (Table 8), and are working though the data to distill it into specific design ideas and important home-modifications that may be necessary. At the time these data were collected, the EPW design had been prototyped and reviewed by several stakeholders in India. The open-ended feedback and accessibility rating has impacted the design of the second prototype; specifically, the second prototype includes a narrower base and a tilting seat, features which were suggested by of many of the phase II subjects.

In the future, we believe this type of online tool can be used throughout the design cycle. In the initial stages of the design project, when a needs assessment must be performed, a study like the one described here can be very useful to prioritize design criteria. After the initial design criteria have been developed, and generic designs have been developed, an online tool like this one can be used to allow experts to provide further guidance on the design—such as picking specific features.

The methods developed in this study are related to user-centered and participatory design (PD) approaches used most commonly in the design of computer interfaces [39, 64, 72-75]. All of these methods include the user, to varying degrees, in the design process. The principles of PD suggest that the designers (engineers, computer scientists, etc.) operate and are comfortable with a certain domain of technical development and design tools. Likewise, the end-user of a product also operates in a 'user' domain where he or she has specific tendencies, needs, and desires. PD offers tools to the users and designers to operate in a 'third' or 'hybrid' space where their domains of expertise may or may not overlap [74]. The ultimate goal is to streamline the development of products so that they can be optimally designed to meet the users' needs and desires. The risk of leaving the users out of the design process can result in costly and time-consuming redesigning and a host of other issues. In one example, Bravo [76] demonstrated the high costs on the health and efficiency of clerical workers when they are not included in the design of their own work-stations.

In PD and user-centered design, a user is considered to be the expert on his or her own needs and desires. In the study described here, we have split the *users* into two groups: those who photographed their environments in India, and those who rated the Indian photos. We considered the photographers experts on the accessibility barriers they face, but because EPWs are so rare in India, we could not expect the photographers to have enough background in the technology to provide actual design advice. Instead, we recruited a second group of *users*—consumers in industrialized countries who are familiar with the current and past EPW designs on the market, and would have some understanding of the technical boundaries of the devices.

We plan to expand this research approach in two ways. First, we intend to distribute disposable cameras in several sites around the world to better categorize the accessibility barriers in both developed and developing countries. Second, we plan to introduce actual design tools into the online survey, so collaborative design can occur between the photographers, and the subjects viewing the photos, and the researchers. The broad-reaching goal is to develop tools where we can put collective expertise and motivation to work to help design improved mobility devices and AT for less-resourced environments.

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5.0 DEVELOPMENT OF A LOW COST ELECTRIC POWERED WHEELCHAIR FOR INDIA

5.1 INTRODUCTION

There are no comprehensive guides on how to design assistive technology (AT) for developing countries, even though there is an overwhelming unmet need. Several organizations design and/or transfer AT to developing countries, especially manual wheelchairs (MWCs) [2, 3] using disparate methods. The majority of these organizations are charitable foundations, endeavoring to meet the needs of disabled individuals worldwide. In some cases they refurbish donated MWCs (e.g. [41]) and distribute them worldwide. In other cases, organizations design low-cost wheelchairs which can be mass-produced and bulk numbers can be distributed to target regions [7, 77]. Still other organizations, like Whirlwind Wheelchair International and Motivation Charitable Trust, setup local wheelchair factories, where designs can be field-tested and streamlined in developing countries so that they can effectively meet the needs of the users in their environment (e.g., [78], [79]). Both of these organizations have transitioned from strictly small-scale manufacturing, to medium and large-scale manufacturing mechanisms.

Despite these efforts, there only a small portion of the estimated 65 million individuals worldwide have access to wheelchairs [4, 28]. There are many reasons for this. First, it is likely that the efforts are not broad enough [6]; assuming a three year lifecycle of wheelchairs, a substantial increase in capacity would need to be achieved to meet the long-term needs. Second, there is substantial anecdotal [2, 6, 15, 16, 20, 44, 46, 50, 51] and scientific [10, 11] evidence that the low-cost hospital wheelchairs, most commonly distributed, fail prematurely or otherwise go unused. Third, the uncoordinated efforts of the organizations working in this sector [48] can be competitive [20], working against their common goal. Lastly, past and present efforts to provide wheelchairs in developing countries are rarely documented in detail (Chapter 2, [53]). Thus, the factors leading the success or failure of these projects are only (possibly) understood by the organizations that performed the projects. This stifles capacity building in the sector, since new organizations do not have any best-practice guidelines (or other relevant literature) on how to design and/or distribute devices for these countries.

Some organizations have described their general approach in the literature [19, 20] and have even published their wheelchair design [22]. Other wheelchair designs have been published in useful guides [40, 80], as well as special seating techniques [81]. Mulholland and colleagues published the most comprehensive series of articles on the R&D of a mobility device for developing countries. In their first paper, Mulholland describes an assessment performed in India [33] to understand the needs of Indian women with disabilities. Their second paper [31] details the design of a mobility device to meet the needs of the Indian women. In their final paper, Mulholland describes the focus groups that were performed with the appropriately designed device [32]. Although she performed a thorough needs assessment, she found that there were mixed responses to the device. The outcome of the work—whether the device is produced and sold in India or any other countries—has not been published. While this is the most thorough account of the design and development of a mobility device in developing country, Mulholland focused on the usability aspects of the device, and did not investigate whether it could be manufactured and for what cost. Also, the mixed responses to the device may have been due to fact that all of the design iterations occurred in Canada, and only the final version was tested in India.

With manual wheelchairs, these uncoordinated and unguided efforts may soon end. Recent efforts by the World Health Organization (WHO), the United States Agency for International Development (USAID), and the International Society for Prosthetics and Orthotics (ISPO) to develop guidelines [4, 28] on wheelchair provision in developing countries. Participants from several organizations have written the draft guidelines; this included several organizations that use rigorous product development methods. While the guidelines are based predominantly on heuristic methods rather than unbiased research evidence of what methods produce the best outcomes, it should establish many of the important steps on how to usefully design and provide wheelchairs for and in developing regions.

These wheelchair guidelines will be published at an opportune time, given the recent passage of the UN Convention on the Rights of People With Disabilities [5] which will require member states to provide affordable and high-quality mobility devices to citizens who could benefit from them (Article 20). These global policy initiatives, the groundswell of student interest in international development, (e.g., [82, 83] and low-cost effective methods to communicate worldwide [84] set the stage for potentially global collaborative design and development initiatives to develop and improve AT worldwide. While the WHO guidelines are likely to make significant strides to improve the low quality MWCs, which are prevalent in developing countries, there are few examples on how to design new products for these regions.

One of the most important factors for developing new products is to identify product opportunity gaps (POGs) manifested due to the social, economic, and technologic (SET) situation in a region [85]. An understanding of the SET variables in combination with knowledge of users' needs and wants can dictate POGs that are both feasible and can have an impact in the market. As part of a larger project our laboratories has been involved with in India ([3], Chapter 2), we have identified a POG in the electric powered wheelchair (EPW) market. There is a tremendous need for mobility products among the estimated 10.6 million individuals with locomotor disabilities in India [9]. While many could be served by high-quality MWCs meant for rural terrain, our experience has been that predominantly low quality hospital-style wheelchairs are available. This situation manifests a scenario where, if a low-cost, high quality EPW were designed and marketed, it may meet the need of a broad consumer group including people with amputations, paraplegia and quadriplegia.

The goal of this work was to pursue this POG, with a methodically designed EPW, which meets the economic, social, and technological constraints of India. Our main goal in this project was to develop a low-cost appropriate EPW for India. Secondarily, we pursued this well-documented product development project to grow the small body of literature in this field, and motivate others to build on our experience.

We performed this project in three phases. The first phase was dedicated to understanding the economic and technologic constraints in India and developing initial design criterion for the EPW. The second phase focused on initial testing of a proof-of-concept prototype in India with stakeholder groups. The first and second phases were considered a feasibility study for the design. Based on our outcomes from these phases we continued into a third phase, where we investigated whether the EPW we designed significantly impacted the mobility capacity of a person with a disability in both open-ended and directed tasks similar to what has been used in another study [86, 87].

In the third phase, we hypothesized the following:

(1) Wheelchair users would travel a significantly further distance when driving the EPW as compared to their MWC during 3-4 hours of their typical daily activities.

(2) Subjects with tetraplegia maneuvering through a pre-defined obstacle course would require significantly less assistance, travel significantly faster, and find the course significantly easier when using the EPW compared to their MWC.

(3) Subjects with paraplegia would find traveling through the outdoor portion of the obstacle course significantly easier with the EPW compared to their own EPW.

5.2 METHODS

5.2.1 Phase I: Preliminary Work

Before entering into a formal design phase, we took preliminary steps to understand the technical and economic requirements for a successful EPW in India. Our first step was to develop preliminary design criterion based on our own experience in India, and the guidance of a mechanical engineering research intern who is native to India, and living in India. These design constraints covered the presumed obstacle climbing, size, and seating requirements as well as a target retail value.

Our second step was to focus more closely on the economic constraint, and perform a preliminary market analysis using a recent Indian Census [9]. The goal of the market analysis was to predict the potential size of the wheelchair market if the EPW was priced at US$1000, $750, and $500. We made several assumptions to accomplish this. First, we used the percentage of EPW users in the US population [35] to predict the expected overall market size. Second, we assumed that a family would buy and EPW if they could afford financing the device over a three year period with their disposable income. Finally, we assumed that if families were eligible for a government subsidy for wheelchairs [23], they would use that subsidy to offset the price of the EPW.

Our final step in the preliminary design phase was to perform durability testing on candidate electric motors for the EPW. Through a related design project with and Indian company, we were able to procure three electric hub-motors, which are very low cost and widely available in India. We performed ISO 7176 [26] tests one of the motors, and retrofitted the other two motors to an Invacare M50 EPW frame. We chose the M50 as a test-bed because it is low-cost, and has impressive obstacle climbing ability [53] (Chapter 3).

5.2.2 Phase II: First-Generation Design and Prototype

Based on results of the market analysis, and conversations with colleagues in India, we quickly realized that market size was highly sensitive to the retail price of the EPW. Even if the lowest cost EPWs available in the US and Europe were transferred (which is slowly starting to occur), they would be prohibitively expensive for many potential EPW users. Due to this price constraint as well as evidence that the low-cost EPWs available in the US had sub-standard quality (Chapter 3, [53]), our primary design goal was to reduce costs without sacrificing the quality and maneuverability of the device.

Table 9 Drive and Control system estimated costs for a Scooter, and an EPW. Abbreviations are: DC = Dynamic Control; Fr = Fracmo

	Device	
	Scooter	EPW
Controller	$50 DC R Series	$220 DC A Series
Drive System	$440 Fr PoV trans-axle and motor	$450 DC EPW Motors
Total Cost	**$490**	**$670**

We focused our cost-cutting efforts on the power and control system, since they account for a large portion of the overall device costs. Quotations from respected companies for these components for both an EPW and a Scooter (Table 9) demonstrated the need to focus on a novel drive system for our EPW. After discussions again with our colleagues in India, we decided to specifically concentrate on a design which was steered manually, but could be upgraded to a power-steering system. Manual steering devices allow for a lower-cost scooter controller to be used.

This approach is not novel, as there are several examples of manual-steering mobility devices. A scooter is steered by a manual tiller system, but it does not provide supportive seating, is unstable in turns, and has poor indoor maneuverability. Other devices, such as one proposed by Laura Clark at the University of Virginia [88], are add-on devices for manual wheelchairs. These types of add-on units are available world-wide (including India), but are not appropriate in the rough terrain of India and other developing countries.

Based on this information, we revised our original design brief to focus on a manual steering device, which uses a hub-motor and can maneuver in the rough terrains of India. A first-generation design was drawn in Solidworks (Concord, MA) and met all design criterion. Fabrication of the device was performed in the US in December and January 2006. We wanted the first-generation prototype to be a fully functioning prototype, built using low-cost material, and easily-adjustable so performance could be tuned without additional fabrication. To accomplish this, much of the device was built using unistrut, which is commonly used in commercial construction applications, allows for easy adjustment, and is available at low cost. To reduce costs, we used a seat from an old EPW (Invacare M50) and used the controller off of a salvaged scooter.

After fabrication was complete, we shipped the device to India and performed focus groups with potential users, manufactures, and clinicians. User and clinician focus groups were performed during International Spine and Spinal Injuries Conference (ISSICON), a yearly conference held at the Indian Spinal Injury Centers (ISIC), in New Delhi. Manufacturer focus groups were performed at the Artificial Limbs Manufacturing Corporation of India (ALIMCO), in Kanpur. Our goal was to collect feedback from ten individual in each of the three stakeholder groups. After recruited subject had given informed consent, we demonstrated the EPW and allowed them to try the device. Subjects were then asked to rate the device using a Likert scale on aspects including the features and aesthetics of the device (Appendix A), and were interviewed on video-tapes to gather open-ended feedback. These focus groups were aimed at establishing feasibility for the proof-of-concept design, and not at evaluating its performance while in operation for the users.

5.2.3 Phase III: Second-Generation Design and Prototype

After feasibility of the design was established through India focus groups, a second prototype was designed and fabricated. We implemented design changes that were suggested in India, especially with respect to the steering system. We also integrated feedback from a user-driven camera study that we performed in collaboration with ISIC in New Delhi (Chapter 4.0).

In contrast to the 'proof-of-concept' first prototype, we constructed the second prototype as a pre-production model so that stakeholder groups in India could evaluate the performance and manufacturability of the device. All parts of the EPW were custom-built in the HERL workshop, using low-carbon tubular steel as the frame and seating structural components. We excluded using any fabrication tools that would not be widely available in India, such as Computer Numeric Controlled machines (CNC) or rapid prototyping methods.

In January 2007, focus groups were performed in the US with five subjects to gather feedback for last-minute refinement before the prototype was transported to India. We recruited five subjects with prior experience with EPWs, and after informed consent, we demonstrated the features of the device. The subjects were then asked to perform several driving tasks in the device, including (1) approaching a sink and turning on the water, (2) entering/leaving a bathroom, (3) driving over rough terrain, (4) driving up/down a ramp, (5) entering and operating an elevator, and (6) driving over speed-bumps. After each of the tasks, a series of questions were asked evaluating the difficulty of each task (Appendix Section 1.01(a)(i)A.2), and what design changes would be useful to improve the device while performing the task.

A final interview and questionnaire (Appendix Section 1.01(a)(i)A.1) was used to record general feedback about the device. User testing of the device was performed at ISIC in February – April 2007. We recruited potential EPW users (n=27) in an IRB approved comparison study. After informed consent was given, demographic information was collected from each subject, and the Craig Handicap Assessment Technique- Short Form [89] was collected to evaluate socioeconomic status. After completing the enrollment, the subject was scheduled to participate in the study for two days within the span of one week. During the first day, we attached a datalogger [90, 91] to the subject's manual wheelchair which non-invasively recorded the distance they traversed for 3-4 hours during their typical daily activities around ISIC. After the datalogging was completed, the subject was asked to complete a 100 meter obstacle course (Figure 11), which included both indoor and outdoor tasks.

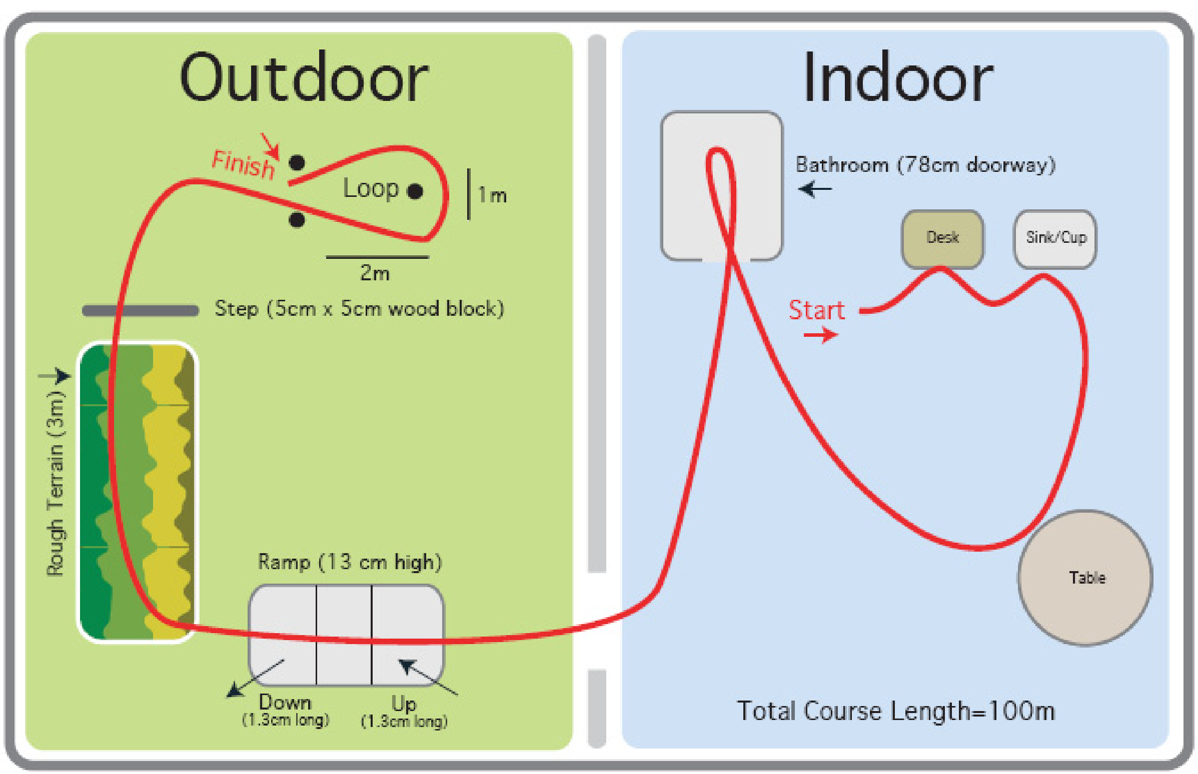


Figure 11. Obstacle course layout at ISIC

Each subject was asked to perform the obstacle course 3 times, and the duration of each trial was recorded using a stopwatch. Subjects were given assistance when they requested it, and the researcher noted how many times assistance was provided during each trial. After the first and third trial, the subject completed a questionnaire, (Appendix A.3) which had a series of 14 cm horizontal lines for each task in the obstacle course. The subject was asked to place a mark along each line according to how difficult the task was to accomplish (where a mark toward the leftmost end of the line meant the task was easy) (Figure 12)

Ex: How hard/easy was it to drive the EPW up to the table?

EASY -- HARD

Figure 12. Difficulty rating scale for each task in the obstacle course

The identical protocols were followed for the second day of the study, although the subject used the EPW rather than their own manual wheelchair for their daily activity tasks and the obstacle course trials. Most commonly, the researcher met the subject in the morning and demonstrated the EPW controls and other features. The subject then transferred into the device and the seating system was adjusted until the subject was comfortable. The datalogger was fixed to the wheel of the EPW and the user was allowed to carry out their daily activity tasks in the device. In the afternoon (typically after lunch), the subject would return and navigate through the obstacle course three times. After completing the third trial of the obstacle course and required questionnaires, a final questionnaire (Appendix A.1) was administered to the subject to gather directed and open-ended feedback about the EPW from the subject.

5.2.4 Data Reduction

Descriptive statistics were used to present demographic information from all phases. Apart from final questionnaires (Appendix Section 1.01(a)(i)A.1), which report in a bar-graph for all phases, no statistical analyses were performed for Phases I & II.

Several statistical methods were used to analyze data generated during the Phase III focus groups in India. We used a two-tailed paired-sample t-test to determine if subjects drove further during their daily activities while using the EPW compared to their own MWC. Because normality requirements were not satisfied, we used non-parametric statistics (Wilcoxon rank-sum [71] to test if trial duration was sensitive to repeated trials, injury level, and device used.

A single researcher used a ruler to measure the location (in millimeters) of the marks the user placed along each of the horizontal lines of the questionnaire to gauge course difficulty (Appendix A.3). The data were digitized and three cumulative 'difficulty' scores were calculated: and indoor, outdoor, and complete course. Because of non-normality, we used a Wilcoxon rank-sum test to determine if there were significant differences in the perceived difficulty of the obstacle course between the first and third trials, which would indicate a learning effect. We also used a Wilcoxon rank-sum test to determine if the cumulative scores (total, indoor, and outdoor) were sensitive to the device used and injury level. Finally, we used Wilcoxon rank-sum tests to determine if the number of times a subject needed assistance was sensitive to (1) whether it was their first or third trial, (2) the device they were using, or (3) their injury level. In all cases, if there was an indication of a learning effect, the data was re-analyzed using only information from the third trial, which was considered the most reliable.

5.3 RESULTS

5.3.1 Phase I: Preliminary Work

The preliminary design brief, developed by an Indian native who is familiar with both EPWs and the built and un-built environments in India is presented below:

1. Minimum Safe climbing angle: 12° (ramp angles common in Indian Hospitals)
2. Turning radius: Less than 20" (space present in traditional Indian houses)
3. Ground clearance: 4" (height of obstacles on the road)
4. Overall Dimensions: Length 35" (approx.) with footrest; Width – 20"
5. Obstacle climbing height: 5" (sidewalks/footpath height)
6. Wheelchair weight capacity: 230 lb (max weight of normal Indian adult)
7. Modular and adjustable construction (removable seat, footrest, armrest)
8. Large Casters (around 9" size) to improve stability and maneuver capability
9. Suspension to adapt to the terrain
10. Cost < $800
11. Large Drive Wheels (around 16") with deep-treated pneumatic or gel-filled to increase traction and ride-comfort

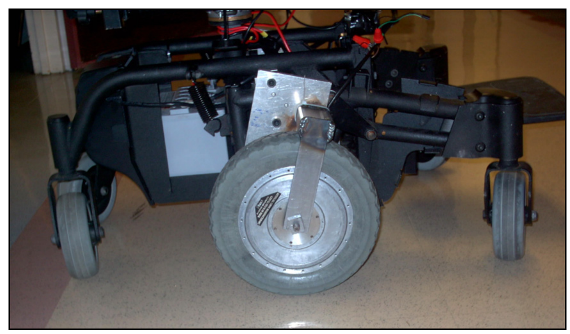


Figure 13. Hub motor adapted to an Invacare M50

Using target prices of $500, $750, and $1000, our market analysis predicted the size of the EPW market in India would be would be 152, 68, and 36 thousand units, respectively. Using the number of units and sales price, these values indicate the market could be worth $76, $51, and $36 million US dollars respectively.

Based on our past experience with low quality Indian Steel [38], our final step of Phase I was to evaluate whether candidate motors from India would be durable and feasible for an EPW design. We found that the hub motors were a sufficient replacement for higher-cost gear motors when we adapted them to an EPW frame (Figure 13). When we performed simulated ISO durability testing on the same motors, we found that the axle-strength was not sufficient to sustain the abuse from ISO testing (Figure 14).

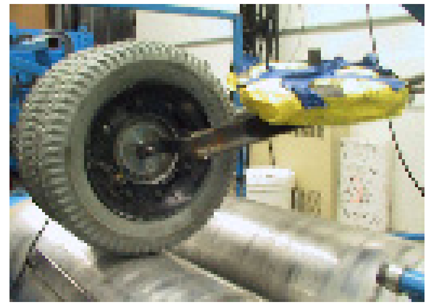


Figure 14. Candidate Motor for EPW being durability tested

5.3.2 Phase II: First-Generation Design and Prototype

The first generation prototype was completed in January 2007 and shipped to New Delhi, India. Because of the use of spare parts (seat, and controller), the cost of the prototype was below $500. A 250-watt hub motor (model #280-1342M, Xti Hub Motor, Rogers, AK, USA) was mounted to a swing-arm system in the mid-line of the EPW (Figure 15). One end of the swing-arm pivoted about the large free-wheeling (back) wheels. The second end of the swing-arm attached to caster links through a captive spring system. The caster links pivoted about the unistrut frame using a shackle system, and 6” casters where bolted to caster forks. Load from the user is distributed between the casters and the hub motor nearly equally. Furthermore, since the force balance must be maintained, the caster constantly tracks over rough terrain, maintaining contact with the ground, as well as applying downward force to the hub motor. The steering arm projected from one armrest in front of the user and was operated by either pushing or pulling the handle. A wigwag throttle was incorporated into the bottom of the steering arm as the throttle. The steering arm swung away to allow for transfers. We accomplished our goal to have several of the design parameters adjustable in the first prototype (Table 10 & Figure 15) of the device. Adjustments were made heuristically to maximize performance before the EPW was shipped to India for focus groups.

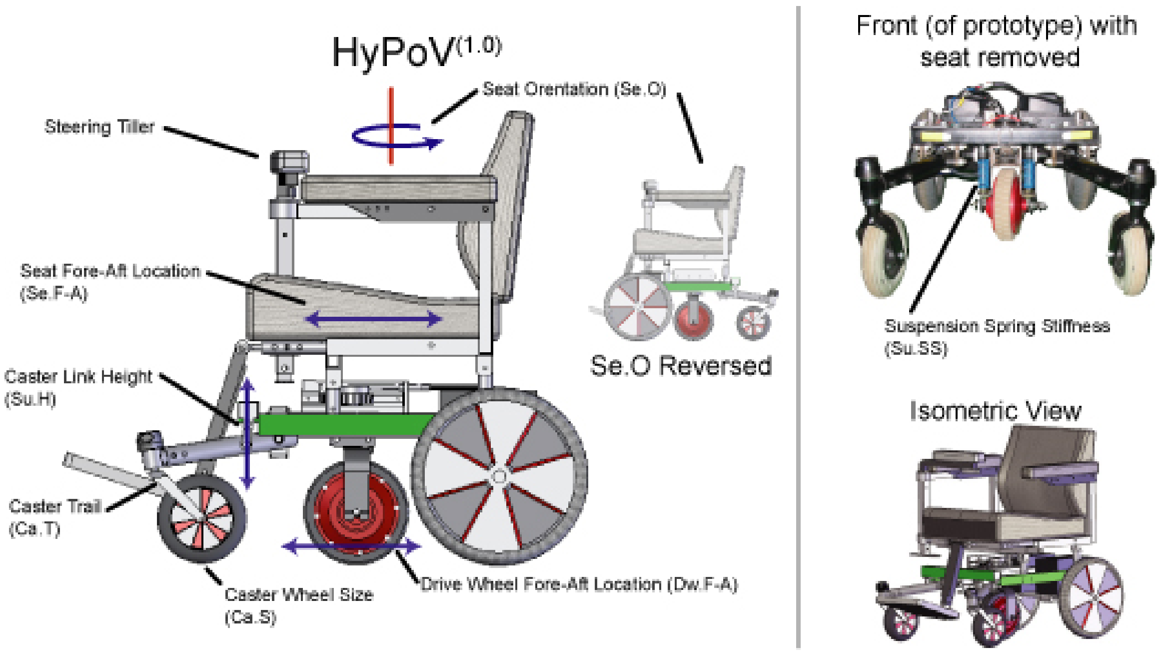
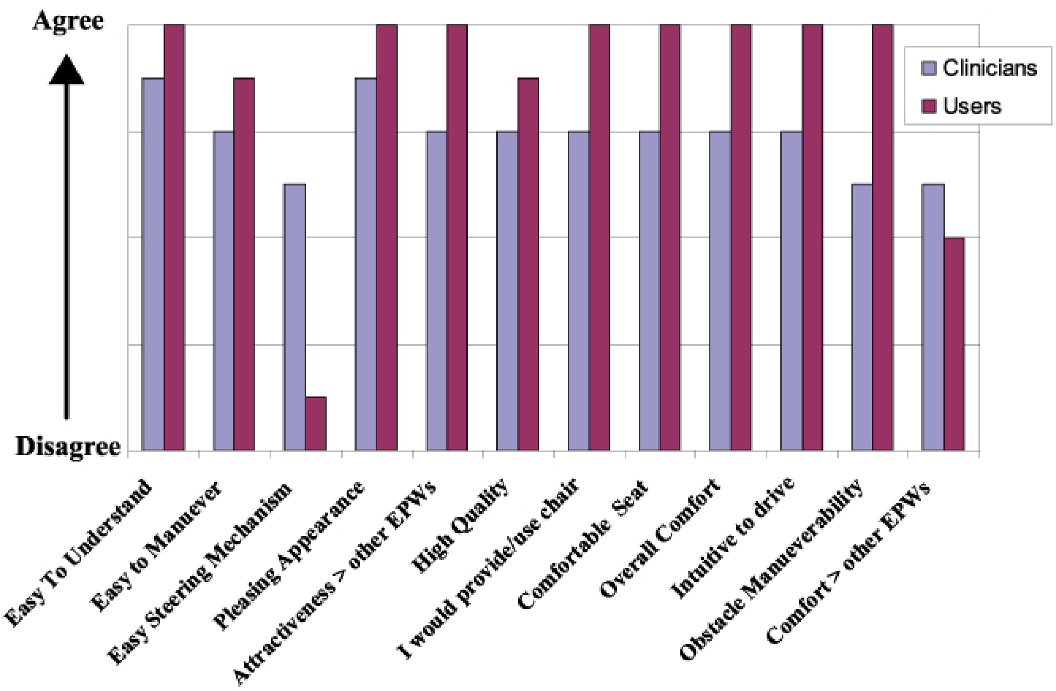


Figure 15. 3D Cad renderings of the HyPoV showing adjustable design parameters

Table 10. Adjustable Design Parameters and the related affect on performance.

Component	**Adjustability**	**Performance Characteristic(s) Affected**
Seat	For-aft location (Se.F-A), Orientation (Se.O)	Stability, traction
Drive Wheel	For-aft location (Dw.F-A)	Traction, turning radius, stability
Suspension	Caster link height (Su.H), spring stiffness (Su.SS)	Obstacle climbing ability, traction, dynamic stability, caster tracking
Caster	Size (Ca.S), trail (Ca.T)	Obstacle Climbing ability, caster tracking
Steering tiller	Steering Sensitivity (St.SS)	Maneuverability, dynamic stability

Twenty-nine subjects (10 users, 10 clinicians, 9 manufacturers) participated in the focus groups and tested the device. User and clinician feedback was mostly encouraging about the device (Figure 16, Top) except for the steering system, which most subjects found was too stiff. Open-ended discussions about the steering system suggested it would be difficult for many users who had trunk-instability, since they would not be able to both push *and* pull the steering arm to turn. Users and clinicians did not have any strong opinions regarding the comfort of the EPW and how it compared to other EPWs they had tried. Manufacturer's had mixed, and in some cases, conflicting opinions about the EPW (Figure 16, bottom). While the manufacturers were confident that they could fabricate and sell the device in India, they thought the overall price and the components would be expensive and many would need to be imported. Manufacturers were generally neutral about whether they could fabricate the steering system and whether the EPW had a pleasing appearance and was comfortable.



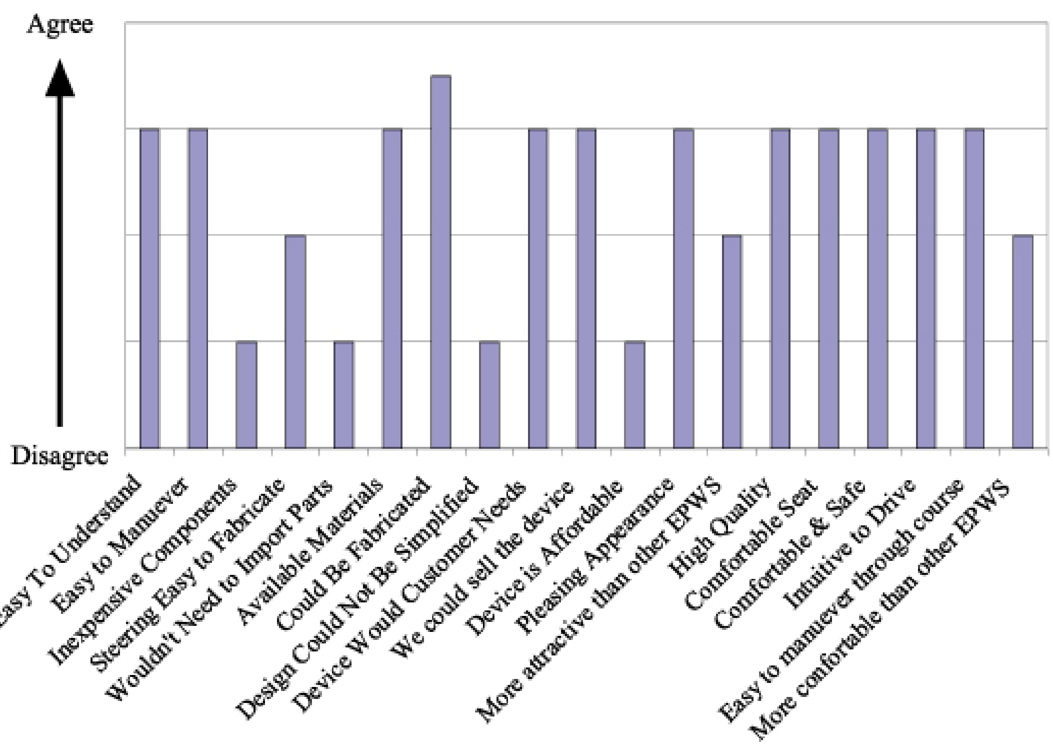


Figure 16. Median clinician, user (Top) and manufacturer (bottom) responses to final questionnaire during Phase II focus groups.

5.3.3 Phase III: Second-Generation Design and Prototype

Using feedback the feedback from Phase II, as well as information gathered from our camera study (Chapter 4), we re-designed and fabricated all parts of the second prototype (Figure 17). Based on the clinician and user feedback (Figure 16, top) we completely redesigned the

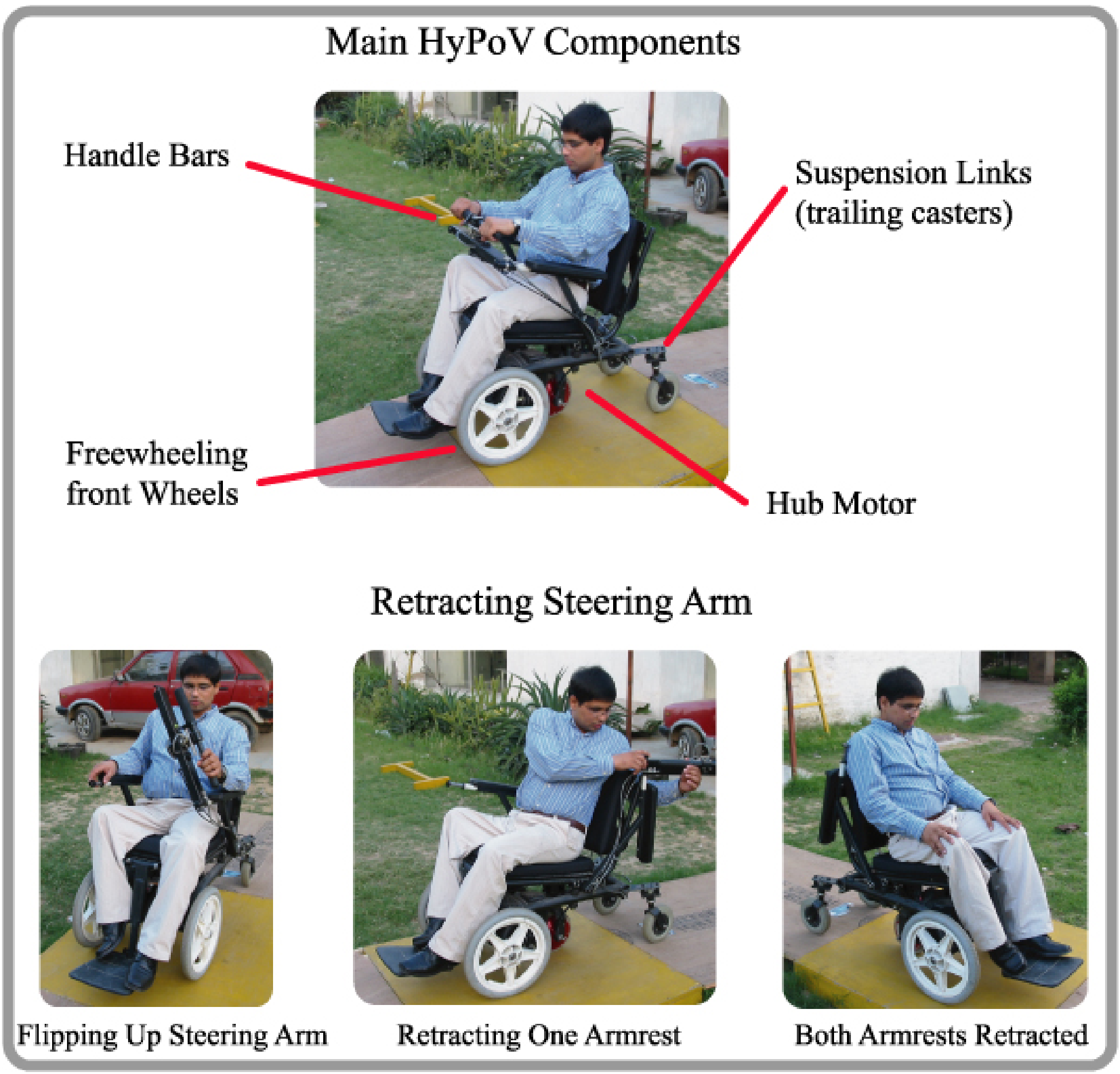


Figure 17. Main HyPoV components and retractable armrest features

steering system to use a handlebar control. This allows the EPW to be steered with two hands (one pulling, one pushing) which helps the user maintain trunk balance. The mechanism uses two bicycle brake cables to transmit direction from the user to the steered hub-motor. A fully retractable steering arm and armrests allow for unencumbered transferring into the device, and also provides the user clear access in front of them when not driving (Figure 17, bottom).

Figure 18. Tilt feature on the HyPoV

Based on the feedback from the camera study, we narrowed the base of the wheelchair by, and reoriented the seat so that the larger wheels were in the front of the device, allowing for better obstacle climbing ability. Design specifications are listed in Table 11.

Table 11. Specifications of the HyPoV $^{2.0}$

Spec	Value	Notes
Turning Radius (cm)	91.4	
Length, Width, Height (cm)	130, 57, 89	Overall Dimensions
Mass (kg)	77	
Distance on full charge (km)	43.1	
Max Speed (m/sec)	1.65	
Max Obstacle Climbing Ability (cm)	7.6, 2.5	Forward, Rearward

A tilting seating system was also incorporated into the device based on camera study feedback

(Figure 18). The five subjects (2 male, 3 female) recruited for the US focus groups in January 2007, had an average of 14.5 (+/ 16.0) years of experience with wheeled mobility products. Based on the open-ended feedback during each trial, design upgrades were performed immediately (whenever possible) before the next subject tested the device. Four primary design adjustments were made during the focus groups: the seat was moved forward relative to the base to increase rearward stability, the handlebars were extended to reduce steering stiffness by increasing the user's leverage on the steering mechanism, an optional twist-throttle was added, and a stop was integrated into the steering arm to limit the travel when it is flipped out of the way. Feedback on the final questionnaire from the US subjects (Figure 19, oblique hash) was positive except related to the ease of steering, the appearance, and how intuitive it was to drive.

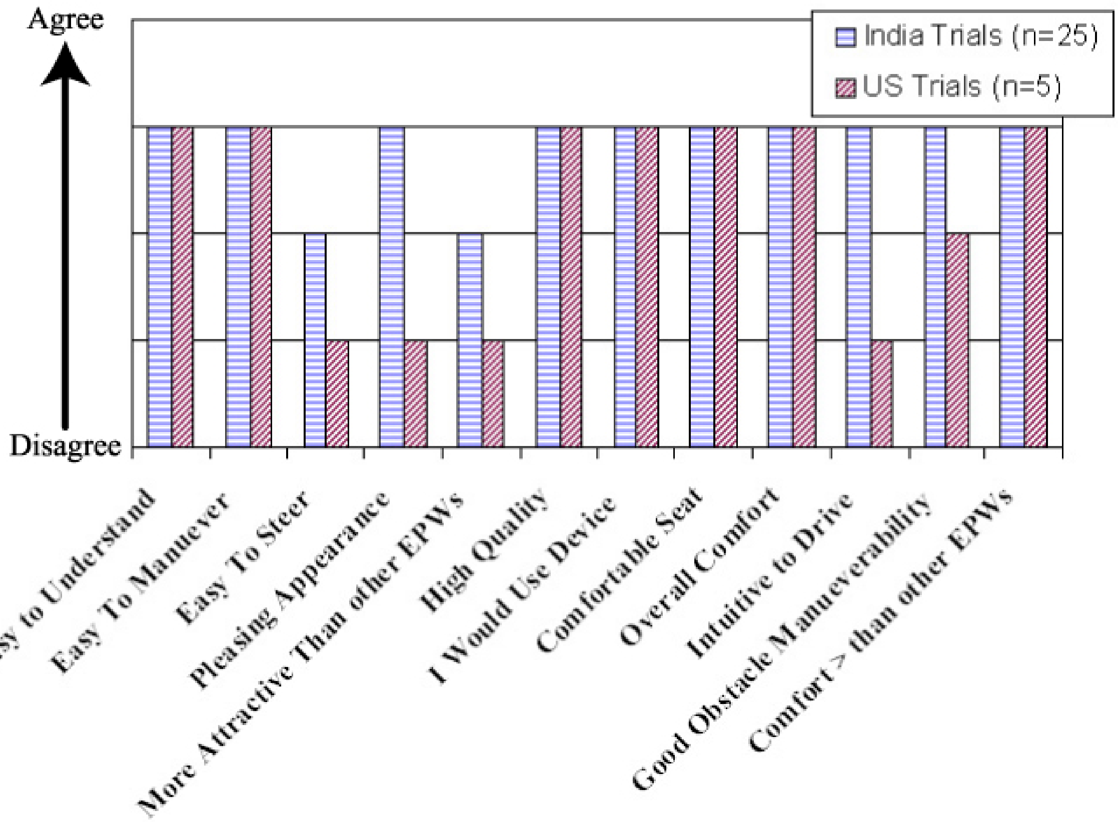


Figure 19. Median responses of subjects to Likert questionnaire in the US and India for Phase III

Twenty-seven subjects were recruited to participate in the trials at the Indian Spinal Injuries Center (ISIC) in New Delhi, India (Table 12). A total of twenty five subjects completed the study; after enrolling, two subjects found it difficult to take time out of their work schedule to visit ISIC for two days.) Of the subjects, the majority were inpatients (19), and the rest were split among outpatients, employees, and non-affiliated individuals. A summary of the statistical findings is below (Table 13). We found that subjects drove significantly further when using the EPW for 3-4 hours of their daily activities compared to driving their MWC. We also found that subjects with tetraplegia needed significantly less assistance when using the EPW compared with their MWC; this was not the case for subjects with paraplegia.

When comparing trial times for the three repeated trials (with a repeated measures ANOVA), and questionnaire responses between the first and third trial (with a Wilcoxon rank-sum), we found most variables significantly different regardless of the mobility device used (EPW/MWC) or impairment level (Tetra/Para), suggesting a learning effect. Thus, we performed statistical analysis only on the results from the third trial, assuming that the data were approaching a steady state. When testing the third trial, we found that subjects with tetraplegia rated the entire obstacle course as significantly easier with the EPW compared to the MWC. Subjects with paraplegia only found the outdoor portion of the course significantly easier. Both of these results are consistent with our hypotheses. We found that subjects with paraplegia took significantly *longer* to complete the obstacle course with the EPW compared to their MWC.

Table 12. Demographics from Phase III India Trials

Parameter	Value
Age: mean +/- SD	20.5 (8.1)
Gender: M, F	20 , 7
Impairment :Tetra, Para	9 , 18
Months Post injury: mean +/-SD	42.5 +/- 64.9
Months of experience with MWC: mean +/- SD	19+/- 28.9

Final questionnaire results from subjects in India were in many cases consistent with US subjects (Figure 19). Overall responses from Indian subject were more positive than their US counterparts. Indian subjects notably rated the device higher in 'appearance' and 'intuitiveness' to drive'. The open-ended question at the end of the questionnaire provided insightful design advice. The most common suggestion was to shorten the wheelbase to reduce the swinging arc

Table 13. Summary of statistical findings from Phase III India trials: A * denotes statistical differences between MWC and EPW values. Course scores were normalized from the full range from 0 to 2100mm to a scale of 0-100 for clarity. Indoor and outdoor scores do not necessarily add to total scores because medians are reported rather than averages.

PARAMETER		MWC	EPW	NOTES
Casual Driving*		193.0+/-98.9	651.4 +/- 346.3	Mean +/- SD meters/hr
Assists	Tetra*	11 (2,14)	2 (2,4)	Median (min, max) averaged number of assists for trial 1& 3
	Para	1.5 (0,5)	2.0 (0,3)	Median (min, max) averaged number of assists for trial 1& 3
Total Course Score	Tetra*	38.8 (3.3, 56.9)	9.8 (1.4, 26.4)	Median (min,max) for Trial 3
	Para	11.3 (0.7, 34.3)	9.5 (0.5, 35.1)	Median (min,max) for Trial 3
Indoor Score	Tetra*	12.3 (0.9, 23.6)	7.2 (0.8, 16.2)	Median (min,max) for Trial 3
	Para	3.6 (0.2, 17.6)	6.6 (0.4, 21.4)	Median (min,max) for Trial 3
Outdoor Score	Tetra*	19.6 (2.3, 38.8)	5.04 (0.6, 10.1)	Median (min,max) for Trial 3
	Para*	9.0 (0.2, 20.0)	1.9 (0.1, 13.7)	Median (min,max) for Trial 3
Course Time	Tetra	317 (125)	227 (65)	Mean +/- SD seconds for Trial 3
	Para*	179 (75)	294 (97)	Mean +/- SD seconds for Trial 3

of the rear casters. Only three of the subjects noted the stiff steering as an issue. The simple seating system was well received—15 of the 25 subjects had no suggested changes, or praised how comfortable the seat was. Several subjects suggested a more supportive footrest. Subjects were generally pleased with the appearance; 7 subjects suggested different colors for the frame, and many subjects suggested add-on features such as a cup holder, cane-holder, and shrouds over the wheels. One subject generically stated that the 'style of the wheelchair' needed to be improved, and another stated that the steering arm was 'ugly'.

5.4 DISCUSSION

5.4.1 Phase I: Preliminary Work

Our preliminary design brief provided a design framework to begin with. While ultimately our design constraints were modified based on stakeholder feedback (Phases II & III) and environmental analysis (Chapter 4), the initial set of design constraints allowed us to identify candidate designs already marketed in developed countries. Based on this initial design brief, we identified the Invacare M50 as our test-bed and adapted Indian hub motors to the frame for initial testing. While there are distinct differences, the SureStep traction system on the M50 was also inspiration for the traction system developed on our EPW.

Durability issues are prevalent with low-cost mobility devices in both developed [13, 14, 53] and developing [2, 10, 11, 15, 53] countries. This literature, and our experience with Indian steel [38] led us to perform simulated ISO testing on candidate motors, which revealed premature failure. Apart from helping us rule out particular motors, developing a protocol for testing allows us, in the future, to specify to manufacturers how devices will be evaluated and what standards they should meet. With the wide range of product quality of devices being manufactured in China, Taiwan, and other countries, it is important to set objective standards to ensure quality is met. While ISO Wheelchair Standards are in place [26], they do not prescribe component-wise testing procedures—which are important in the initial design stages. Because we adapted ISO Section 8 durability testing procedures to component-wise testing, we believe failures at the component-level will faithfully reproduce failures at the device level.

Our preliminary market analysis demonstrated the price-sensitivity of the market. While we made several assumptions to reach our market size, it is highly likely that our findings are conservative. First, the census and income values we used [9] were from 2002. Based on World Bank (www.worldbank.org) data, India's population continues to grow (1.4% in 2005), the economy is expanding at a rapid rate (8.5% in 2005), and inflation is kept to relatively low levels (4.2% in 2005) [92]. This indicates that the growing population is slowly becoming wealthier, making devices such as the EPW more affordable, which will increase the size of the EPW market. In parallel with population and economic growth, India is becoming more accessible due to the Persons With Disabilities (Equal Opportunities, Protection Of Rights And Full Participation) Act of 1995 (PDA)[93]. Public and private transportation such as railway stations, subway stations, and airlines have slowly become accessible to people with disabilities. This increased accessibility will likely broaden the mobility device market, as more people with disabilities can more easily be active members of society.

5.4.2 Phase II: First-Generation Design and Prototype

We were able to fabricate a novel, low-cost proof-of-concept design during Phase II. The highly adjustable design was built out of necessity rather than choice. Because the drive, steering, and suspension system were a unique design, we were initially unsure how the device would maneuver and climb obstacles. Designing for adjustability and symmetry (Figure 15) (e.g., to allow for a reversible seat) facilitated easy 'tuning' of the entire device through the fabrication and preliminary testing phases. We were also able to heuristically identify performance trade-offs (Table 10) for each design parameter, which lends itself to parametric optimization methods. In the future work, we intend to develop a full computational model of the suspension system and use parametric optimization to determine the final design parameters, in order to maximize obstacle climbing ability, stability, and maneuverability.

There are several drawbacks to developing a highly adjustable design. First, adjustability suggests there is hardware (bolts, screws) holding the device together. In our case, the added hardware made the device heavy and less aesthetically appealing than a fully customized welded frame and seating system. Likewise, the frame and suspension system were not as structurally stiff as they would have been if welded, reducing overall performance (maneuverability and obstacle climbing ability). These effects bias the focus group feedback.

Subject responses to our focus groups in India were critical to evaluate the feasibility of the device, and reveal important design changes. Most importantly, we identified the steering system as a critical design flaw. Our initial design was focused on developing a non-invasive steering system that could be easily flipped behind the user. Our first design accomplished this, but also required the user to steer by pushing (right turn) or pulling (left turn) on the steering arm. For individuals with spinal cord injury, depending on the injury level, there are trunk stability deficits, and reduced function of the triceps muscles; this limits the individuals ability to pull (due to trunk instability) and push (due to reduced triceps function), making it nearly impossible for many individuals with higher level spinal cord injuries to drive our first prototype. We rectified this problem by using a balanced steering system in the second phase, where users can push and pull simultaneously on the handlebar to turn in a single direction.

We held focus groups with potential manufacturers to gauge the manufacturing feasibility. Although other projects of this type have not addressed manufacturability directly [31, 32], we felt feedback was necessary with a complex device such as an EPW. The results were mixed (Figure 16, bottom)—although manufacturers agreed that they could fabricate and sell the EPW, they felt the components were expensive and would need to be imported, and that the overall device would not be affordable. The focus group for manufacturers was held at the Artificial Limbs Manufacturing Corporation of India (ALIMCO), a large-scale manufacturing facility in India, which specializes in making low-cost AT for the poor in India. While the company had initially made overtures about introducing an EPW in their product line, their focus is on extremely low cost devices that are built at costs below government subsidy levels (USD125) [23]. Thus, their response, especially related to affordability, may reflect their company's bias toward selling inexpensive, low-tech AT. What was most important and revealing was their confidence in being able to fabricate the device using available materials. Based on more recent information, we know of several importers of the parts that are not manufactured domestically (specifically the motor and controller), which can be purchased, in bulk, for low costs in India.

5.4.3 Phase III: Second-Generation Design and Prototype

Phase II results and our camera study (Chapter 4) informed our design changes, guiding us to improve the steering and seating and also the dimensions of the device. Our second device was custom-fabricated, fixing many of the adjustable parameters and substantially reducing the number of fasteners. Apart from the re-designed steering and seating system, we simplified the suspension system by using leaf springs in place of the rigid suspension links and captured spring system on the first prototype. This design change increased rigidity of the suspension system, significantly reduced the number of components, and was simple and low-cost to fabricate. We demonstrated the device to two local manufacturers during focus group testing, and both suggested they could build the device for approximately $450, and make a profit if they sold it priced at $550, closely achieving our goal of a $500 device. Several of the specifications of the HyPoV were measured based on ISO 7176 standards [26] and are shown in Table 11. Based on energy consumption tests (ISO 7176 Section 4[26]), the $HyPoV^{2.0}$ can travel a total of 43.1km on a single charge Table 11. This value suggests the HyPoV can travel, on average, 48% and 31% further than low-cost [53] (Chapter 2) and higher-cost [56] EPWs, respectively. We did not perform several pertinent tests, such as static stability (ISO 7176 Section 1) or Static Strength, Impact and Durability (ISO 7176 Section 8) although this is the subject of future work.

We had a large subject population in comparison to similar studies [32, 86, 87] (15 and 8 subjects, respectively). Our breakdown between men and women (Table 12) (m=74%, w= 26%) is similar to the breakdown in the population of people with disabilities in India (m=62%, w=38%); in the future, we hope to make more of an effort to recruit woman so the sample can be more representative. A majority of our subjects were inpatients at ISIC, and had recently been injured. Although all were out of acute care, many had little experience with MWCs and were propelled by assistants (regardless of injury level). Although this is atypical for users in the US and European countries, data suggests the majority of individuals do not self-propel their manual wheelchairs [10, 11]. This is due to several reasons, inclusive of, but not limited to, the poor quality MWCs in India, the lack of user training, and the low-cost of a personal assistant (~$2.50/day). We agree that with proper training and improvements in wheelchair quality (as suggested by the WHO [4], Chapter 1), MWC users could be more functionally independent, but these improvements are likely far in the future. Meanwhile, the market for wheelchairs is dominated by low-cost, low-quality hospital style wheelchairs which limit independent mobility.

The summary of our statistical findings (Table 13) demonstrate several relative improvements when subjects used the EPW compared with their MWC. First, subjects traveled significantly further, per-hour, when they were driving the EPW, compared with their MWC. We attribute a portion of the relative increase (~450meters/hr) on a 'novelty' effect of driving a new device. Regardless, each subject had a daily schedule of tasks to accomplish (whether it was physical therapy or job-related tasks), and so drove the EPW more during their free time. In many cases, the subject would roam outside, up and down ramps, and socialize individual in wards that otherwise were difficult to access because they were not independently mobile in their MWC. In many cases, their assistant would accompany them initially during their EPW driving walking behind the EPW (it cannot be pushed), but in many cases, the assistant would leave, allowing the subjects to move unencumbered. While the comparison between the distance traveled in the EPW and MWC is telling, even more telling were the qualitative observations of the users in the EPW—they seemed excited to roam outside and speak with others; they generally seemed happy to be independently mobile, made positive remarks about the device, and commonly asked when it would be available for sale.

Comparison between the obstacle course assists, difficulty ratings and course times were similarly telling of the EPW performance (Table 13). Individuals with tetraplegia required significantly less assistance during completion of the obstacle course and found the course significantly easier to accomplish when using the EPW. There were no significant differences between the course times with the EPW and MWC for subject with tetraplegia. Taken in the context of the significant reduction in assistance for individuals with tetraplegia in the EPW over their MWC, these results suggest the EPW effectively replaces a paid assistant, and makes tasks significantly easier.

We found that subjects with paraplegia felt the outdoor portion of the obstacle course was significantly easier to accomplish with the EPW compared to their MWC. While this result may be surprising, the poor quality of MWCs available in India and the lack of wheelchair skills training significantly limit outdoor mobility. This is troubling, considering nearly 75% of individuals with disabilities live in the rural environments [9]. We also found that subject with paraplegia took significantly longer to complete the course in the EPW than in their MWC. The reason for this is likely the indoor speed at which individuals with paraplegia can complete the obstacle course in their MWC. The course was setup in the physiotherapy lab, which is ideally accessible (except for the bathroom doors, which have spring-closing systems). Most subjects were very familiar with approaching the desk, sink, and table; and entering the bathroom in their MWC, so the individual tasks themselves were not demanding. When using the EPW, the front-wheel drive maneuverability of the device slowed many subjects indoors.

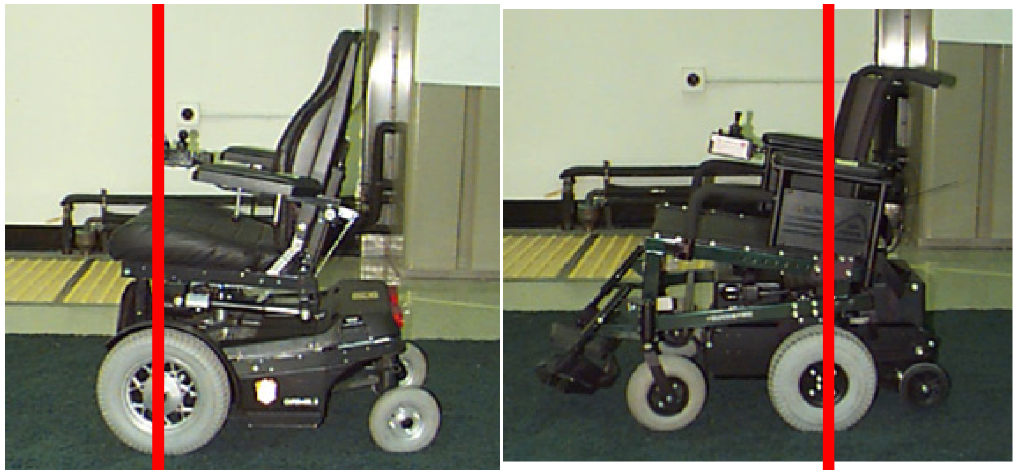


Figure 20. Point of rotation for front wheel drive (left) and rear wheel drive (right) EPWs

Subject feedback on the Likert portion of the final questionnaire was revealing especially when compared to feedback by the US subjects (Figure 19). In general, Indian subjects rated the EPW higher than their US counterparts. All responses from Indian subjects were positive except for the question related to ease of steering and attractiveness, which were rated as 'neutral' (neither agree nor disagree). Despite the issues Indian subjects conveyed with steering the device (discussed more below), they found the EPW substantially more intuitive to drive than the US subjects. The steering system on the EPW mimics a motorcycle, with a twist throttle and handlebars. While motorcycle use is relatively uncommon in the US, motorcycles and mopeds are ubiquitous in India. Similarly, low-cost taxis ('auto-rickshaws') are driven with an identical steering and throttle control system. This is an example of how the societal differences have a significant effect in the response to product design [85].

During the Phase II focus groups, the small casters were located in front of the device. Based on trials with the seat reversed, we found obstacle-climbing ability to be much improved when the seat was reversed, and so the Phase III prototype was fabricated with the large diameter wheels at the front of the device. The consequence of this design change is reflected in the open-ended comments from subjects on the final questionnaire. By switching the orientation of the seat, the device maneuvers like a front wheel drive EPW (Figure 20), where the device rotates about a point approximately between the user's knees. This gives the sense that the EPW is very long, since the rear portion of the device swings in a wide arc during a turn. Given that few of the subjects had driven an EPW before, especially a front-wheel drive design, they were more comfortable with how an automobile steers (which is similar to how a rear wheel drive EPW steers). Thus, the feedback that the wheelbase should be shortened from many of the subjects (which was not given when the seat was reversed), indicates that possibly the seat should be oriented in its original position. This original orientation (Figure 15) also allows for the users' feet to be placed between the suspension links, effectively shortening the overall length of the device.

The HyPoV was designed for an adult population although there is a tremendous need for pediatric mobility devices world-wide. Bias towards the adult population stems the fact that a parallel design effort is being made to develop a low-cost pediatric wheelchair for Indian users. Since the HyPoV is a 'power-base' EPW [12, 94] the design does not prohibit placing a seating system appropriate for pediatric clients. Adapting the product for pediatric clients is the subject of future work and would likely require re-design of the tiller-system to allow it to be mounted either in front of the user (for users with good upper-arm motor-control) or at an alternate site to allow an assistant to drive the wheelchair.

5.4.4 Conclusions

People with disabilities deserve high quality mobility devices so they can be more independent and participate more fully in society. Already implemented [93] and upcoming [5] policies in developing countries will help in this vein, but there are still substantial technological challenges to overcome that will ensure devices meet the social, economic and technical constraints in developing countries. To leverage the skills of rehabilitation specialist and engineers world-wide, along with the growing interest among students in talking international development projects, it is important to build a wider body of published experience-based knowledge of the research and design approaches that are successful and unsuccessful in these countries; this will help avoid situations like the repeated failures of MWCs technology transfer to meet the needs in developing countries [2, 6, 53].

The project described here has been successful in developing a low-cost appropriate EPW for individuals in India. The device will likely be appropriate in many developing countries, with slight design changes to accommodate the parts and materials, which are locally available. Despite the strong performance of our design, a more comprehensive engineering analysis could have been performed to optimize the steering and obstacle climbing ability of the device prior to user trials. We plan to perform this analysis for the next prototype.

To complete the project, we plan to perform in-home trials of the EPW after design modifications have been integrated based on our Phase III results. We may perform these trials independently, although we feel that it is best to collaborate with a manufacturer to fabricate the prototype device so that user-feedback can be integrated directly into the product design cycle.

6.0 CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

A shift is starting to occur in the world. Brought on by improved communication technologies, people are not only able to see what is occurring around the world through television and photographs, etc., but they are also able to communicate world-wide, and make personal efforts to affect positive change in the world. In some cases, these efforts can be misguided—they try to effect positive change, but ultimately do not improve situations, or in some cases, worsen them. This scenario has plagued the transfer of AT to developing countries for the past several decades; individuals and organization with good intentions have been transferring AT to developing countries that have not been designed or tested to determine whether they meet the needs of the user in their environment. Consequently, many of these devices do not meet the users' needs, fail rapidly, or cause injury.

Anecdotal reports of these AT failures and their implications on the health of PWD have attracted the interest of international organizations that are aiming to stem-the-tide of inappropriate AT and provision. The WHO, USAID, and ISPO are publishing guidelines which describe best-practices related to wheelchair technology and provision [4, 28]. The UN recently passed the Convention on the Rights of People With Disabilities [5], which has implications on the selection and quality of AT that is provided to PWD in all countries.

The collective efforts of these organizations will have an important policy impact. But to actually implement the changes described in these documents, rigorous research and design methods need to be employed: outcome studies need to determine 'which' technologies are appropriate, and rigorous approaches need to be in place for the design and development of AT to ensure it will meet the needs of the user. While anecdotal accounts are a guide to the types of research questions that need to be asked, they are subject to bias and thus do not form a rigorous understanding of the problems or solutions.

Several organizations already produce appropriate technology that is well fitted to the user. In the wheelchair sector, both Motivation Charitable Trust (Bristol, UK), and Whirlwind Wheelchairs International (San Francisco, USA) are well-respected for both their high-quality technology, and their impressive clinical provision techniques; all of the workshops and clinical service providers that they have started worldwide are models of how appropriate wheelchair provision can be successfully transferred to a developing country.

These models provide important examples, but as discussed in the Chapter 2.0 , they represent only a small portion of the potential methods to transfer wheelchairs (and other assistive technology)—there are several other potentially valuable techniques which have not been proven yet. Furthermore, the methods used by these groups are heuristic, and are not described well in the literature, making it difficult to replicate these projects. Lastly, any outcome studies performed by these groups (and others) have not been published, so it is difficult to assess how well they are performing. These facts build a scenario where there are successful AT tech-transfer projects demonstrated, but there is a lack of a framework that describes how to perform them in the future, and how to assess their outcomes.

In Chapter 2.0 , a framework was proposed to describe the different types of tech-transfer approaches for transfer of wheelchairs. While the focus of this framework was on wheelchairs, we believe it can easily be expanded to incorporate other families of AT. We also proposed four abstract factors (input, appropriateness, sustainability, and output) that could be used to describe the value of any given tech-transfer project. Metrics, which would allow measurements of these factors were left un-defined, although proven method used elsewhere (e.g., metrics to evaluate business sustainability and to evaluate the user satisfaction with AT) may prove useful in the context of developing countries. The thesis of Chapter 2.0 was expanded upon in a publication led by the author, in collaboration with experts who have performed AT tech-transfer to developing countries on several occasions [95]. In that paper, we compared transfer of lower extremity prosthesis (LEP) and wheelchairs to developing countries, and found that the genesis of LEP transfer began similar to how wheelchair tech-transfer has been proceeding over the last two decades. With LEP, the technology did not improve until standards and guidelines were put in place and enforced worldwide. Chapter 2.0 and the associated publication [95] help form a framework and suggested methods on how to perform the research necessary to develop rigorous standards.

The final Chapters (3, 4 & 5) discuss different portions of a case-study to design, develop, evaluate and transfer an EPW to India. The ANSI/RESNA [24, 25] and ISO testing [26] discussed in Chapter 3 seems like the logical first step when screening technology for transfer to developing countries, but because these standards are not enforced in most developing countries, much of the AT that is being transferred to, or being built in a developing country, has not been tested. Some organizations that purchase AT from large-scale manufacturing facilities rely on those facilities for quality assurance. But in some cases, these manufacturers may test to their own national standards, which may be less rigorous than the ISO standards (for example, Indian and Chinese national wheelchair standards are much less stringent than ISO). Thus, the work described in Chapter 3 demonstrates an important first step when choosing candidate technology for transfer to developing countries. Not only do the results suggest low-cost EPWs would not be appropriate for developing countries, the results also demonstrate that the majority of these EPWs did not meet the ANSI/RESNA standards mandated by the US Food and Drug Administration (FDA). In the US, wheelchair manufacturers are allowed to perform their own testing to assure compliance with the FDA. In combination with other publications from our laboratories [13, 14, 55-57], the results described in Chapter 3 suggest the manufacturers may not be completely forthcoming with their testing results. These results strongly suggest that a third-party should be performing the standards testing, whether the devices are for the developed or developing countries.

In Chapter 4, we describe a technique to perform a low-cost needs assessment using a combination of ethnographic methods and an online survey. Information technology (IT) has advanced to the point where people can speak to each other around the world at no-cost through the internet. It is critically important to find ways to use IT to allow developing countries to leverage the resources available in developed countries. Instead of using an in-person method to perform a needs assessment like some have done [33], we developed a tool which combined the low cost of IT and ethnographic methods using a camera study. This enabled us to gather feedback from people worldwide to help in the design of the HyPoV. This study was largely successful—we were able to understand the severity and prevalence of accessibility barriers in India, which helped define the design priorities for our EPW. We collected valuable design ideas for the device, which we implemented in the second prototype (Chapter 5). We also gathered valuable feedback about the survey tool itself from an exit comment-box that was filled in by many of the participants. Negative feedback primarily related to the participants being confused about which accessibility barriers were important to the photographer in the photo. This has guided the development of the online tool and methods for future studies.

Chapter 5 describes the design, development and evaluation of the EPW for Indian users. While one other group has described a mobility device tech transfer project [31-33], the work performed here provides a more comprehensive and step-by step approach to the process. There were several valuable outcomes. First, designing the first prototype to be highly adjustable, and fabricating it with off-the-shelf hardware and materials, kept prototyping costs low. It also allowed for simple design adjustments. These adjustments allowed us to trial the EPW in different configurations, and allowed us to avoid iterative prototyping which can be necessary when non-adjustable prototypes are built. For lower-cost devices, such as simple AT and even manual wheelchairs, an iterative prototype may be useful; but for this more technically challenging product, the adjustability allowed for design changes without rebuilding. The drawback to this approach is that obstacle climbing ability and maneuverability were compromised on the first prototype because of the increased weight of the device, due to the numerous fasteners, and the less rigid frame (because it was bolted rather than welded).

The value of performing the focus groups, both in the US and in India cannot be overstated. During the first round of interview we gathered a substantial amount of data, including the written surveys and open-ended questions, along with video interviews. Because the device did not maneuver or perform to the level of a fully welded prototype, these focus groups may have been more in-depth than necessary. The value of the focus group may have been increased if we had performed a less-comprehensive interview and no user trials. Instead we would have performed a driving demonstration, and gathered data from more subjects about user needs and potential market.

In contrast, the second set of focus groups (5 subjects in the US and 27 in India), were remarkably valuable at providing design ideas, and evaluating the utility of the device for Indian users. The focus groups based in the US provided important last-minute design changes, especially related to the steering tiller. After feedback from the first two subjects, the tiller was modified to incorporate a twist-throttle, and the length of the tiller handle bars was extended by several inches to increase the leverage. These design changes were easily executed in the US, but would have been more difficult to address in India. Focus group participants in the US had EPW experience, which pre-disposed them to assume that the EPW should maneuver and perform similar to commercially available EPWs. Thus, results from this focus group actually had two important impacts on the design. First, several design changes were suggested which improved the usability of the device immediately (for both the Indian and US population). Second, we gathered feedback about the potential issues that may arise if the EPW was developed for the US market, which turns out to be quite different than for the Indian market. Most notably, the tiller steering system was not intuitive to use by the US participants (Figure 19), but was intuitive for the Indian participants. These differences are related to ubiquity of motorcycles and 'auto-rickshaws' in India, which use handle-bars and twist-throttles as the control interface. Most US consumers were use to a joystick, and the tiller system was not natural. This does not prohibit the EPW from being used in countries where motorcycles are rare, it just suggests that sufficient training must be performed to ensure the US consumers can maneuver the EPW safely.

While results from the second India focus groups suggested the EPW dramatically improved mobility and independence of individuals with quadriplegia, and in some circumstances, with paraplegia (Table 13) there is still work to be done to improve the design and transfer of the device. Three manufacturers in India were interested in the design of the device, but ultimately no technology transfer agreement was signed. We suspect there are two reasons for this. First, another design iteration is necessary to improve the performance and stability of the EPW and prove that it meets international wheelchair standards [26]. We felt that companies were reluctant to sign a technology transfer agreement that included provisions for HERL and the company to work together on the design until it reached the production stage. Second, wheelchair manufacturers in India, in many cases (there are exceptions), operate under the assumption that something is better than nothing for their customers; this is both a driving force and a result of the fact that PWD are generally marginalized in India, and policies that ensure equality for PWD are not strongly enforced or known about. As a consequence, several of the companies seemed reticent to adopt the HyPoV because their current products were sufficient (to them) and a new product would require new tooling and costs. Additionally, there were several companies we did not discuss the option of a tech-transfer agreement based entirely on the fact that their current products were sub-standard. Future WcTT projects would likely benefit from having a commercialization partner for the device at or near the beginning of the project. With vested interest in the device being marketed and sold, a commercialization partner may reduce the barriers for WcTT by coordinating manufacturing, marketing, and distribution of the device during the prototyping and evaluation phases.

6.2 FUTURE WORK

There are several research areas that this work naturally leads to. First, as discussed in Chapter 2 and the conclusion section above, standardized metrics need to be developed to evaluate the four important factors (input, appropriateness, sustainability, and impact) that were proposed. Once these metrics have been defined, past and current tech-transfer projects should be analyzed (when possible) with these tools, and future projects should be planned to include these outcome measures. There are currently research studies proposed at the Indian Spinal Injury Center (ISIC) that may address some of these metrics, especially related to the appropriateness and impact factors. The Quebec user evaluation of satisfaction with assistive technology (QUEST) [96] was proposed to help identify the **impact** of AT on PWD. Also, a wheelchair comparison study was proposed to determine whether users go further, faster, and can perform better on a wheelchair skills test [97] with an appropriately fitted wheelchair; this addresses the **appropriateness** factor. If funded, these studies would be the first to objectively evaluate the impact of wheelchairs on the user population in a developing country.

Independent wheelchair testing, as described in Chapter 3, would seem like a natural first-step to identifying and ruling out candidate AT for transfer to a developing country. Unfortunately, these tests can be costly, in part, because the testing equipment is available in only a few locations worldwide. More effort needs to be made to promote testing and other quality-control mechanisms worldwide. The author has been involved in the design and construction of testing equipment in Cali, Columbia, and San Paulo, Brazil. Future work is planned in Ethiopia and India. Meanwhile, documents such as the Wheelchair Provision guidelines [5, 28], will help inspire policies to ensure equipment is safe and functional for the users. More still needs to be done, especially with respect to developing testing equipment worldwide, and, in the absence of this testing equipment, promoting low cost testing. Until this testing equipment and testing methods are disseminated, organizations will still cite the high-cost of performing these tests as a reason for non-compliance.

The study described in Chapter 4 sets an important example of how, using low cost methods, it is possible to leverage the resources of developed countries to help developing countries. The tremendous growth of low-cost information technology has flattened the world [84], allowing for friendships and business relationships to form around the globe. We look forward to leveraging these technologies to apply the vast available resources in developing countries, to problems that need to be solved in less-resourced environments. In this technological age, there is little reason that an engineer or clinician in the US or Europe should be restricted from using their skills to help technicians and health-workers in developing countries through the internet or other information technologies. Technology is not the limiting factor; instead it is that there are few tools developed to allow this transaction to occur. Where there are financial gains to be made (e.g., business sector), these tools are already developed. The field of AT needs to leverage these technological opportunities in order to develop participatory design tools [73], and distance learning tools so that the rich resources of developing countries can be easily passed abroad. In future approaches using online methods, we suggest to directly recruit camera study participants (photographers) for the device user-trials. This will provide direct feedback from the subjects on whether the device meets their needs, and help validate the camera study methods. This will also mimic the typical needs-assessment approach used by Mulholland and colleagues [31-33] and help reveal the drawbacks and benefits of using an online versus in-person approach.

A third generation prototype of the HyPoV is currently being developed—our goal is to make it a pre-production model and perform ISO testing. The primary design change has been included in Appendix B, and addresses an issue with the suspension system that affects the stability of the device. Once the pre-production model is complete, we will seek licensing agreements with manufacturers abroad and in the US. The design is currently protected by a provisional patent in the US, and a full patent application should be submitted in October 2007. There are also plans to formally develop the HyPoV for the US market using the SBIR and STTR granting mechanisms.

The work described in Chapter 5 demonstrates the utility of taking a step-by-step approach to the design, development, and transfer of AT. The methods need further refinement. First, a more comprehensive understanding of the technology available in the target developing country can help avoid designs that could not be built or repaired in that country. We were fortunate to have strong clinical contact in India (through ISIC) but stronger contacts among the wheelchair manufacturers would have streamlined the design process even more. As mentioned above, the first set of focus groups in India were successful, but the methods should be streamlined to increase the number of subjects that were involved, and reduce the burden of collecting video of each subject. A traditional focus group, rather than several independent focus groups, would be more ideal, allowing participants to discuss the design amongst each other, rather than directly with the researchers (as was common in our focus group). This was the initial plan, but because the focus groups were coordinated with the 2006 ISSICON conference, subjects had difficulty participating in single focus groups because of the overlapping plenary sessions.

6.3 CURRENT AND FUTURE POLICY IMPLICATIONS

Technological and political changes worldwide influence the current and future states of WcTT. For example, globalization of manufacturing can have both positive and negative effects on WcTT. The primary impact of globalization on WcTT is that can lower the consumer cost for the device which benefits the end-user and increases the number of individuals who can benefit from the devices. One caveat to this is that there must be competition among manufacturers and distributors if the user will benefit, otherwise they may just increase their profit margins and not pass any savings to the consumer. A second caveat is that there needs to be technical standards for the devices which are built; simply providing more dangerous devices at lower costs will never meet the needs of the users. Since globalization is making it cost-effective for companies who do adhere to ISO and ANSI/RESNA standards to manufacture abroad, manufacturing quality of could potentially improve world wide. Whether these higher-quality devices are also being distributed in countries which do not require high technical standards is not known, but at least large-scale manufacturers will be poised to improve the technical standards once the WHO and UN policies are adopted.

While these policies have tremendous potential to improve the quality of the technical and clinical services provided to PWD, they can only do so if they are paired with rigorous 'field' tools for ensuring high technical quality, appropriate clinical provision guidelines, and appropriate training manuals. Some of these tools already exist. For instance, the ISO 7176 wheelchair testing standards [26] provide wheelchair testing protocols, although they should be modified to ensure the tests reflect the rigorous conditions in developing countries. The International Classification of Functioning, Disability and Health (ICF) [98] can help harmonize the methods to perform needs and outcome assessments, and collect important demographic information. Lastly, the ‘Classification of Technical Aids for Persons With Disabilities’ (ISO 9999) may be useful in harmonize how wheelchairs and other AT are classified and their reimbursement levels in different countries.

Current Indian Government policies have a strong influence on the success and failure of WcTT. First and foremost is that the ISI wheelchair standards that the government-supplied wheelchairs must meet are not rigorous enough to protect against premature failure of manual wheelchairs. This insufficiently rigorous standard sets the stage for low-quality wheelchairs to be built in and transferred to India

Second, India protects its markets through significant import duties; when wheelchair manufacturers from abroad setup distribution networks, or independent distributors purchase from abroad, these duties are passed onto the consumer through increased product costs. Interestingly, if a consumer initiates the purchase of a mobility device for their own use (directly from a foreign manufacturer or distributor), they can receive an exemption. This imbalance rewards the users who are knowledgeable about the intricacies of import policies and thwarts the progress of developing distribution networks of imported devices to be created.

Third, the Indian government ADIP scheme [23] to subsidize the purchase of mobility devices (and services) for low wage-earners is out of date and should be updated to take into consideration a wider range of products (including powered mobility products) and should have higher reimbursements to reflect high-inflation and a rapidly growing economy. If the ADIP scheme reimbursed for higher-cost devices, such as those which are appropriate in the rough terrains of the built and unbuilt environments of India, the end-users would benefit tremendously. Furthermore, if there were fewer barriers to registering for the ADIP scheme (for both the providers and manufactures) then it could be a useful tool to spark innovation and competition in the mobility device field.

APPENDIX A

FOCUS GROUP QUESTIONNAIRES

A.1 GENERAL FEEDBACK QUESTIONNAIRE

FOR PHASE II AND III FOCUS GROUPS

What type of assistive mobility device do you use currently?
Manual Wheelchair ☐
Scooter ☐
Power wheelchair ☐

How many years have you used assistive mobility technology?_______

For each statement below please check the response that best indicates your opinion.

Mechanical features

1) Understanding how the wheelchair works was easy.

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

2) The wheelchair could maneuver easily around obstacles.

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

3). The steering mechanism seems difficult to use

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

Appearance of the wheelchair

4) The wheelchair has a pleasing appearance.

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

5) The chair is more attractive than most Power Wheelchairs I have seen.

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

6) The chair seems to be high quality.

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

7) I would be happy to use this chair.

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

Comfort and ergonomics

8) The seat would be comfortable to sit in for long periods of time.

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

9) Parts of the wheelchair would be in the way when I was doing things around my house, or at work.

Yes ☐ No ☐

If Yes, Which part(s) (put an X for each part that would be in your way).

Big Wheels ☐ Small Wheels ☐ Steering Arm ☐

10) Overall, the chair is comfortable and secure.

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

11) The HyPoV was intuitive to drive

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

12) The device was easy to maneuver through the obstacle course.

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

13) The HyPoV was less comfortable than other wheelchairs I have tried.

Strongly Agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly Disagree ☐

*Considering these 3 aspects of the Electric Powered Wheelchair, is there anything you would change if you could? Please explain your answer***.**

Maneuverability:

Seating:

Appearance:

Thank you very much for your time!!

A.2 PHASE III: US TASK QUESTIONAIRRE

script for researcher to use after each task, and to collect response from subject.

Task: worksite | kitchen | table | bathroom | ramp | outdoors | step | elevator

1) *On a scale from 1-10 how difficult was the task you just completed with **10 being very difficult**?*

1 2 3 4 5 6 7 8 9 10

2) *Did anything on the device interfere with you performing the task?*
If yes, what?

Wheels ____ Steering system _____ Footrest(s) _____ Armrest(s) _____

Seatback ____ Other ____

What design modifications would you suggest to improve this?

---

3) *Did the HyPoV perform as well as you would desire during the task?*

If not, in what way did it not meet your expectations?

____

What performance changes would you suggest.

____

4) *On a scale of 1-10, how comfortable was it to perform the task in the HyPov, where 10 is **most** comfortable?*

1 2 3 4 5 6 7 8 9 10

(regardless of answer) how would you suggest to improve the comfort?

____

5)   On a scale of 1-10, how does the HyPoV compare to your usual mobility device where 10 is much better and 1 is much worse?

1   2   3   4   5   6   7   8   9   10

In what ways could we improve the device to perform better?

____

A.3 PHASE III: INDIA OBSTACLE COURSE QUESTIONNAIRE

Trial 1 _______ Trial 3 _______

To answer the following questions, please put an X to signify how hard or easy you thought the task was during the course.

For example, the answer to a question could appear like this:

Ex: How hard/easy was it to drive the HyPoV up to the table?

EASY --X-- HARD

#1: How difficult/easy was it to enter the worksite area?

EASY --- HARD

Did not complete ___
Completed with assistance ____

#2: How difficult/easy was it to leave the worksite area?

EASY --- HARD

Did not complete ___
Completed with assistance ____

#3: How difficult/easy was it to enter the kitchen area?

EASY --- HARD

Did not complete ___
Completed with assistance ____

#4: How difficult/easy was it to move the cups to/from the kitchen sink?

EASY --- HARD

Did not complete ___
Completed with assistance ____

#5: How difficult/easy was it to approach the table?

EASY -- HARD

Did not complete ___
Completed with assistance ____

#6: How difficult/easy was it to move away from the table?

EASY -- HARD

Did not complete ___
Completed with assistance ____

#7: How difficult/easy was it to enter the bathroom?

EASY -- HARD

Did not complete ___
Completed with assistance ____

#8: How difficult/easy was it to leave the bathroom?

EASY -- HARD

Did not complete ___
Completed with assistance ____

#9: How difficult/easy was it to go up the ramp?

EASY -- HARD

Did not complete ___
Completed with assistance ____

#10: How difficult/easy was it to go down the ramp?

EASY -- HARD

Did not complete ___
Completed with assistance ____

#11: How difficult/easy was it to maneuver over the rough ground?

EASY -- HARD

Did not complete ___
Completed with assistance ____

#12: How difficult/easy was it to go up the step?

EASY -- HARD

Did not complete ___
Completed with assistance ____

#13: How difficult/easy was it to go down the step?

EASY -- HARD

Did not complete ___
Completed with assistance ____

#14: How difficult/easy was it to go around the figure-8 course?

EASY -- HARD

Did not complete ___
Completed with assistance ____

APPENDIX B

SECOND PROTOTYPE DESIGN OF THE HYBRID POWER OPERATED VEHICLE

The following pages contain the completed dimensioned drawings of the second prototype of the Hybrid Power Operated Vehicle (HyPoV). Short descriptions of each of the assembly drawings are presented here. An updated torsion-spring-based suspension system is also included, although prototyping and testing of that design upgrade are the focus of future work.

B.1 OVERVIEW OF DEVICE

The HyPoV is a cross-over design between an electric powered wheelchair (EPW) and a scooter. The device is designed similar to a 'powered base' EPW, and thus can be naturally subdivided into a seat assembly and a frame assembly (which includes drive-train). The seating system includes a seat-base and –back, which are fabricated as a rigid system. The arm-rests and foot-rests attach directly to the seat frame. The tiller system is attached to dowel-pins which are fixed within part of the arm-rest assembly. The manual steering system uses two common bicycle cables wrapped around drums (one on the tiller and one on the hub-motor fork) to turn the hub motor. This hub-steering system is related to the dual-cable systems used on many sailboats, where cables wrap around a hub at the steering wheel, and then actuate a yolk that is fixed to the rudder at the other end.

The seat assembly is attached to the frame assembly at three points using quick-release pins: two of the points are on the lateral portions of the seat-bottom, and form a hinge between the seat and frame assemblies. The third point is located along the midline of the device, and an adjustable-length rod (to change the tilt-angle) is used to attach a point behind the seat-back to the frame.

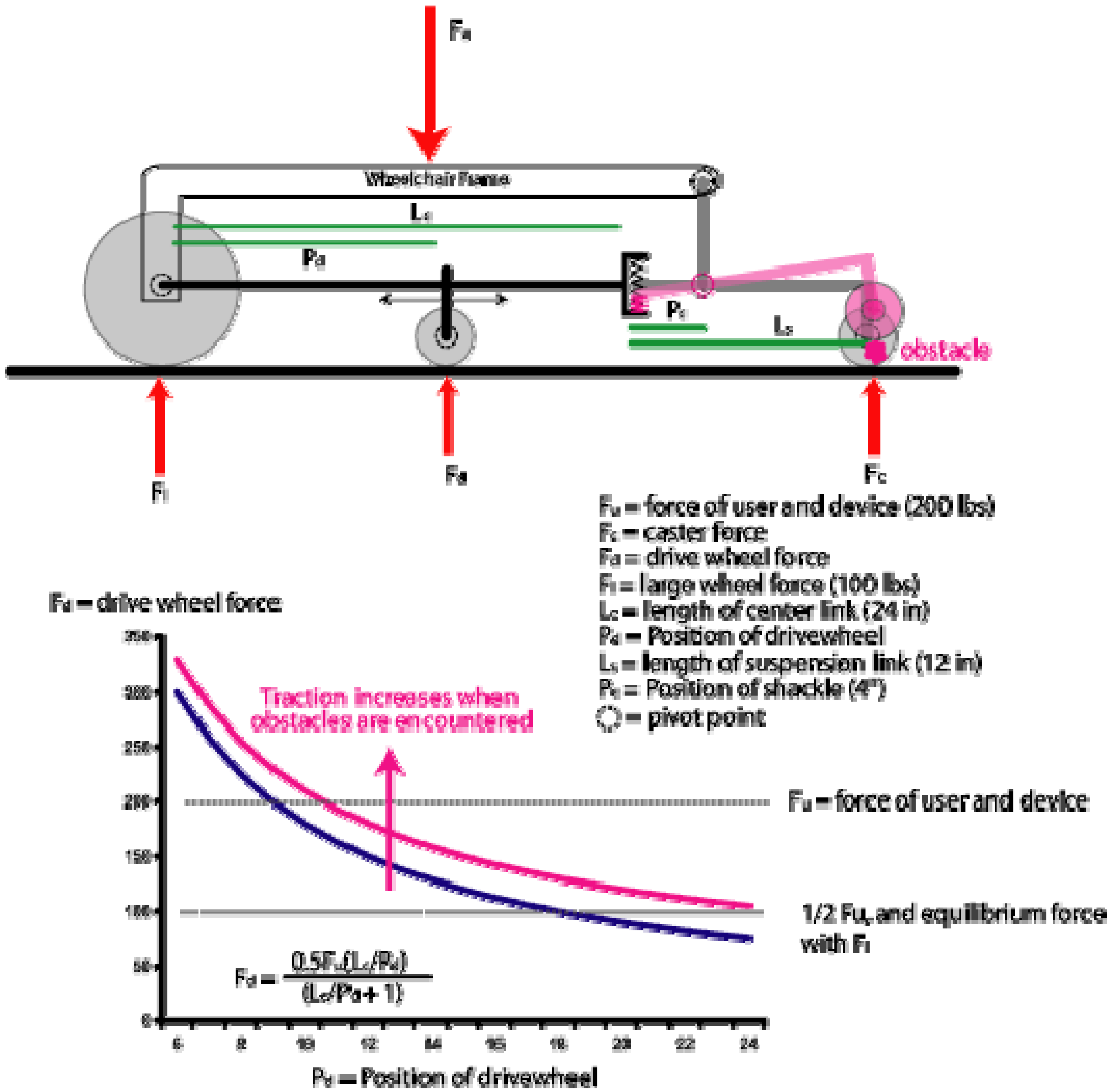
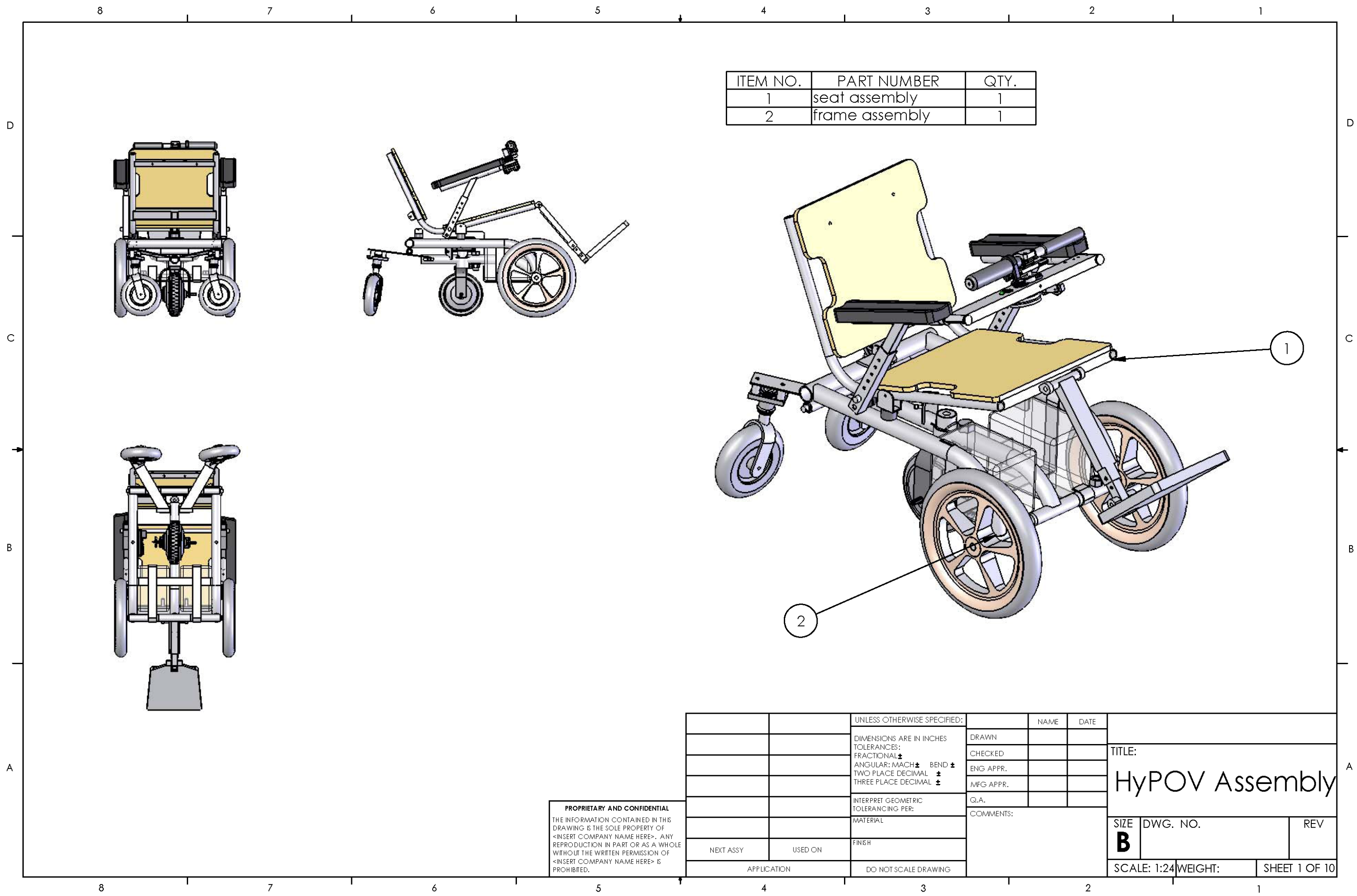


Figure 21: Parametric description of load on the drive wheel due to caster loads and obstacles

The frame assembly includes the leaf-spring suspension system, the centrally located swing-arm (which houses the hub-motor), and the electronics (batteries and controller), and the axle and wheel system. The leaf-spring suspension system pivots on the rear aspect of the frame, and connects caster-wheels to the end of the centrally-located swing-arm. The opposite end of the swing-arm forms a pivot around the axle-wheel system. As mentioned above, the swing-arm houses a hub-motor, which functions to propel, brake, and turn the HyPoV. This swing-arm in conjunction with the suspension system is the distinguishing feature of this device compared to both EPWs and Scooters. As can be seen above (Figure 21) loads applied to the frame from the user and the seat are distributed to the large free-wheels, and the caster and drive wheel through the lever of the leaf-spring (shown as a coiled-spring in the figure). The force balance between the caster and drive-wheel is always maintained (within the travel of the suspension) which ensures a downward force on the drive-wheel at all times. Furthermore, when the caster passes over an obstacle, it amplifies the downward force on the drive wheel, increasing traction.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2 | frame assembly | 1
1
2
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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
HyPOV Assembly
SIZE
B
DWG. NO.
REV
SCALE: 1:24
WEIGHT:
SHEET 1 OF 10
PROPRIETARY AND CONFIDENTIAL
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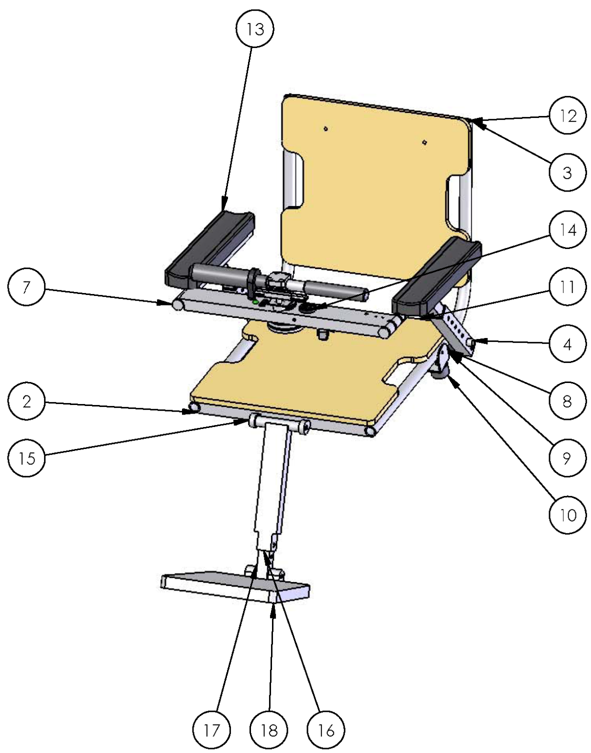
B.2 SEATING SYSTEM

Two round tubes with a bend to form a 110 degree angle are the primary structure of the seating system. These tubes are tied together with four cross-pieces: of the two in the seat-bottom, on acts as the pivot for the arm-rests, and the other supports the foot-rest structure; of the two in the seat-back, one supports a perch which is attached to the adjustable-length rod, and the second is used to secure the seat-back base (wood). The seat-bottom and seat-back base material is wood, notched to allow access to the round tubs which form the seat-frame. These notches allow for lateral support devices to be attached to the seating system (although those devices are not yet designed). Any type of cushion can be attached to the wood to assure pressure-relief. Note that the seating system is drawn so that it is oriented on the frame with the foot-rest sitting between the large 16" wheels. The second prototype was built with this orientation, but the reverse orientation (so that the foot-rest is between the casters) is also feasible and was used in the first prototype. We changed the orientation during the second prototype to take advantage of the fact that the larger diameter wheels require less force to travel over an obstacle than the small caster wheels.



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3	seat		2
4	seat - armrest pivot rod		1
5	seat - cross back		1
6	seat - cross back bottom		1
7	arm rest assembly		2
8	arm rest - bumper		2
9	seat - hinge		2
10	seat - bumper		2
11	seat bottom		1
12	seatback		1
13	arm rest cushion		2
14	tiller mount assembly		1
15	footrest - attachment pin		2
16	footrest - tube outside		1
17	footrest - tube inside		1
18	footrest - footplate		1

				NAME	DATE
		UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
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TITLE:

Seat Assembly

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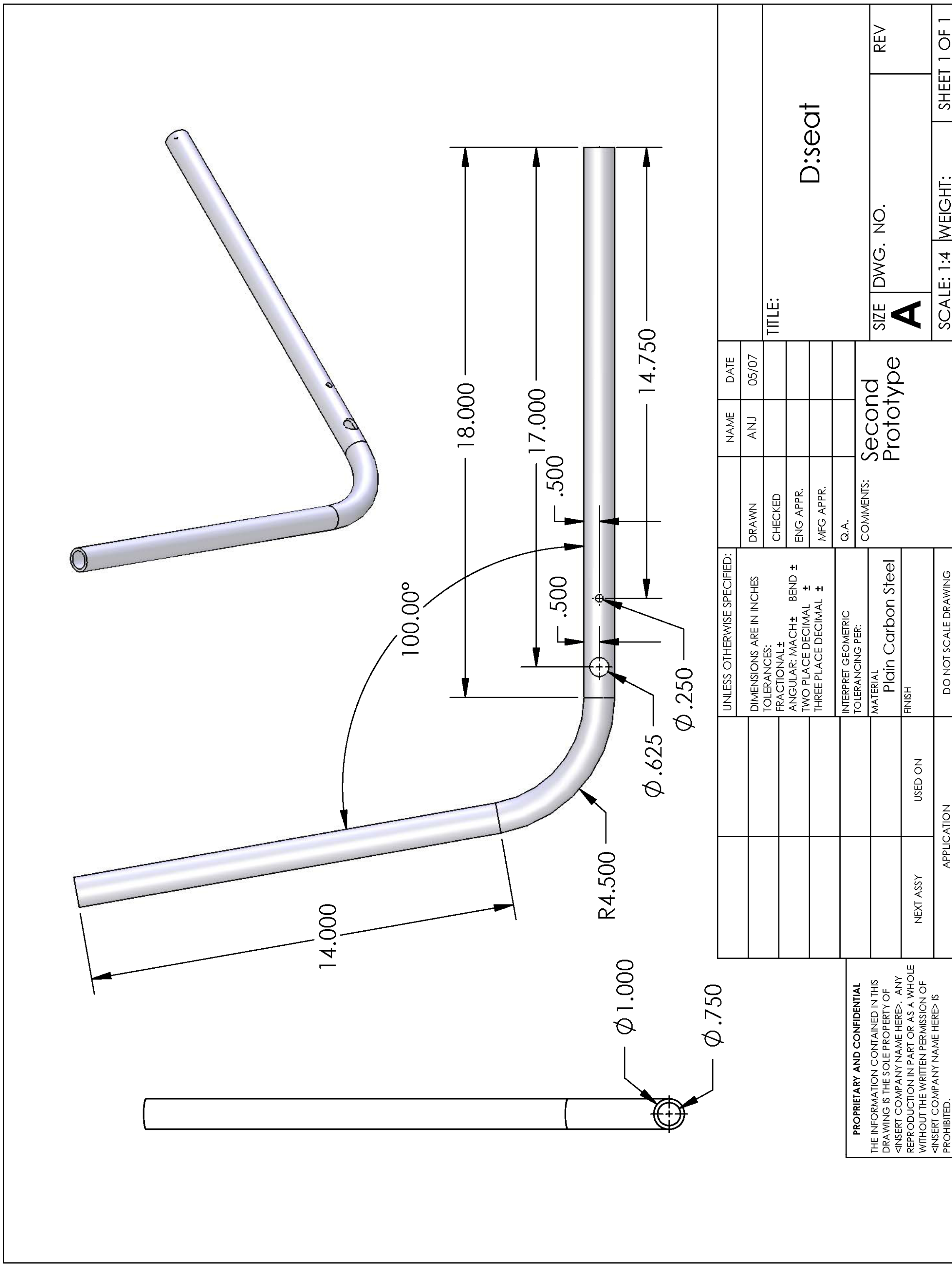

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100.00°
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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:seat
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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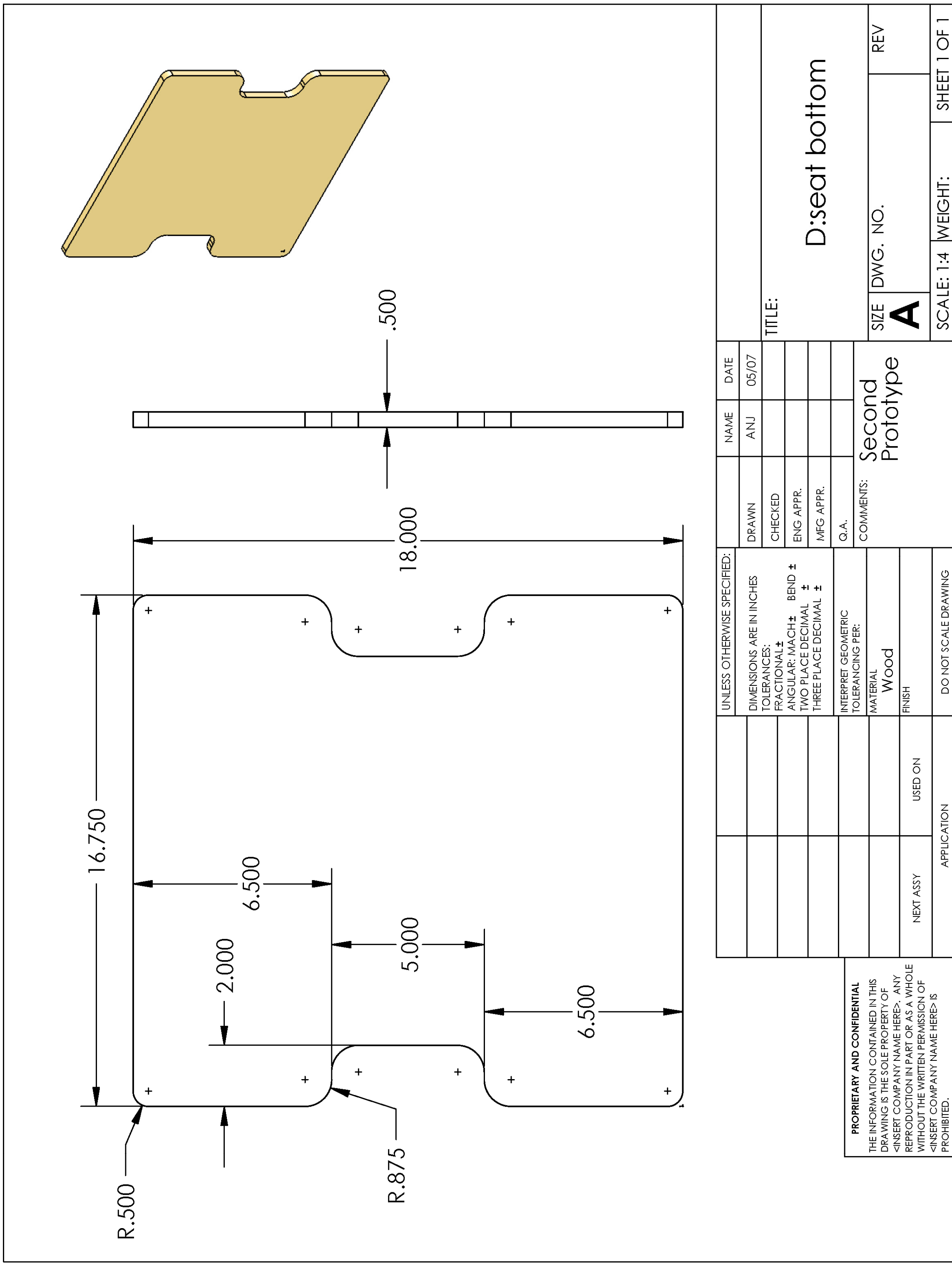
5
4
3
2
1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6.500
2.000
5.000
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R.500
R.875
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TOLERANCES:
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Wood
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
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APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:seat bottom
SIZE
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DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
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4
3
2
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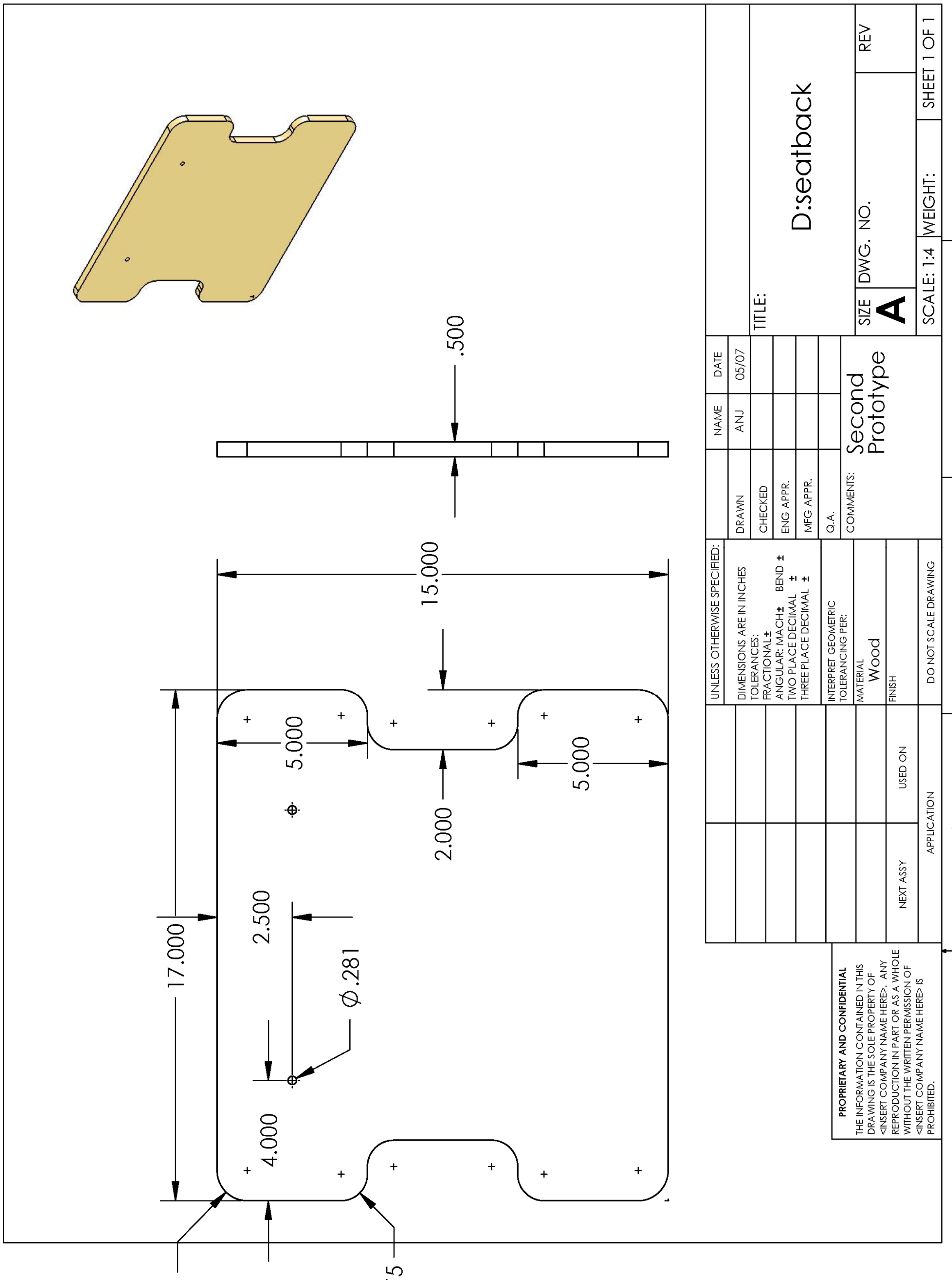
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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Wood
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:seatback
SIZE
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DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
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2
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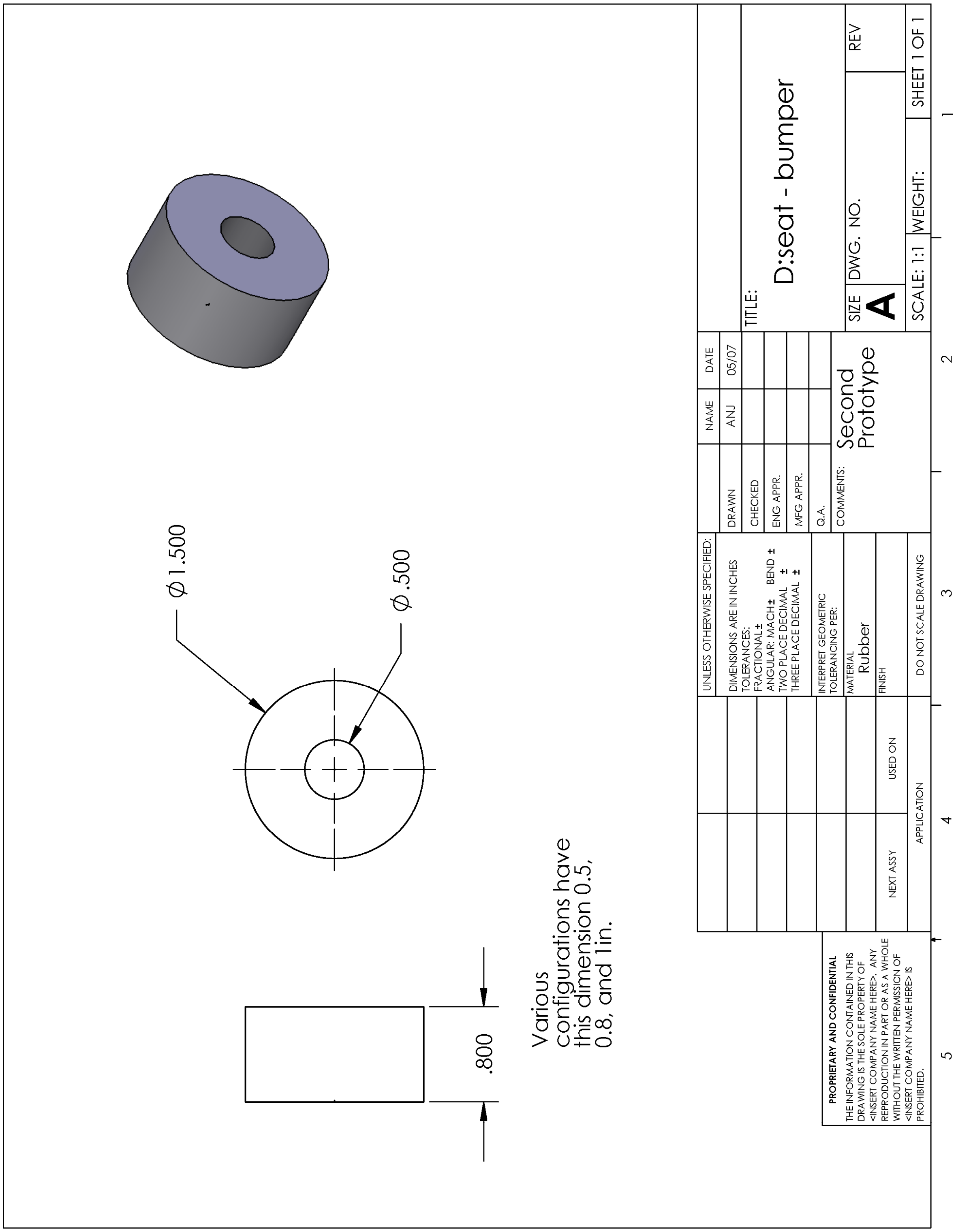
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Ø.500
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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Rubber
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
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REV
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SHEET 1 OF 1
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4
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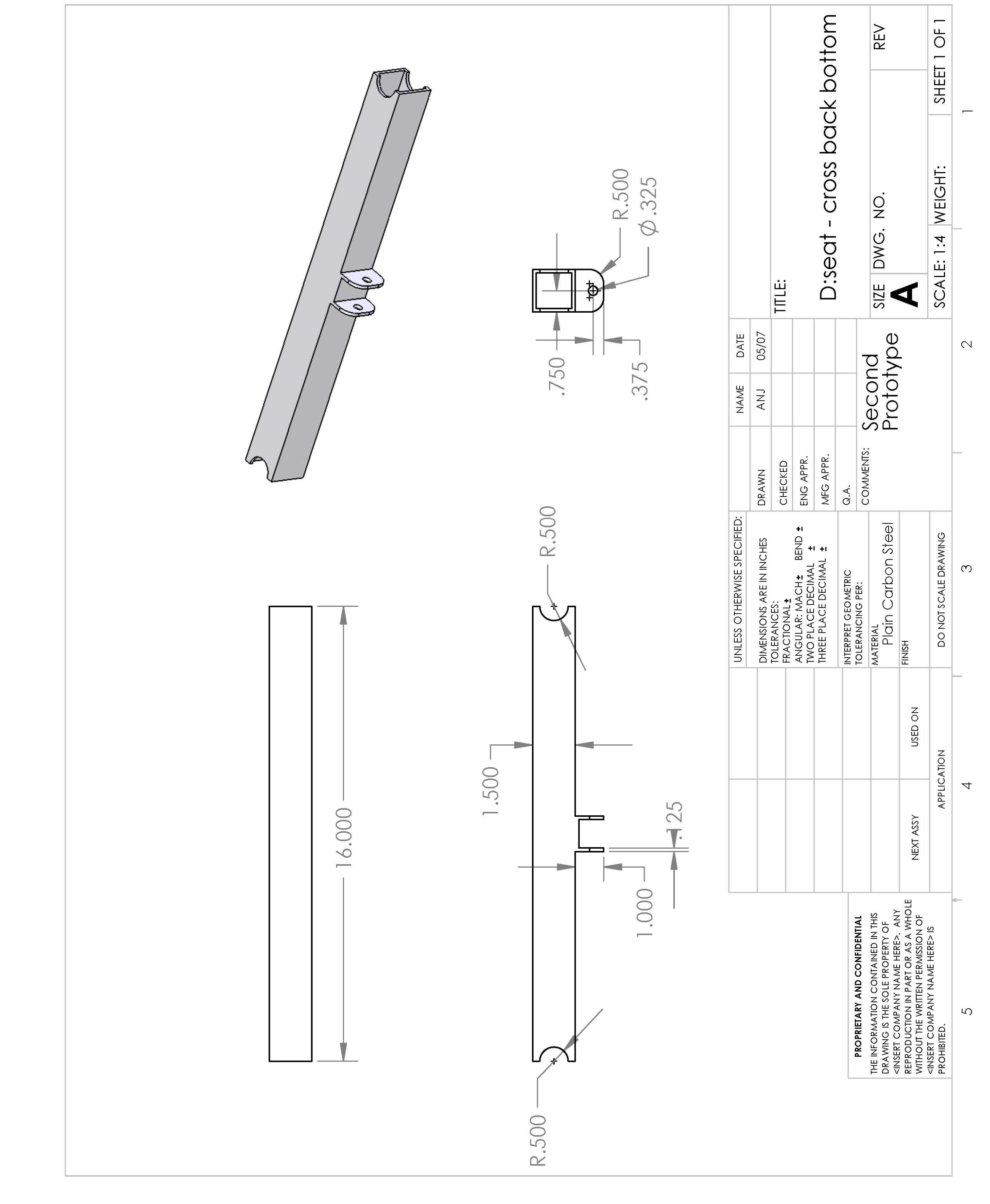
1



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R.500
R.500
R.500
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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
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APPLICATION
NAME
DATE
DRAWN
ANJ
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CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:seat - cross back bottom
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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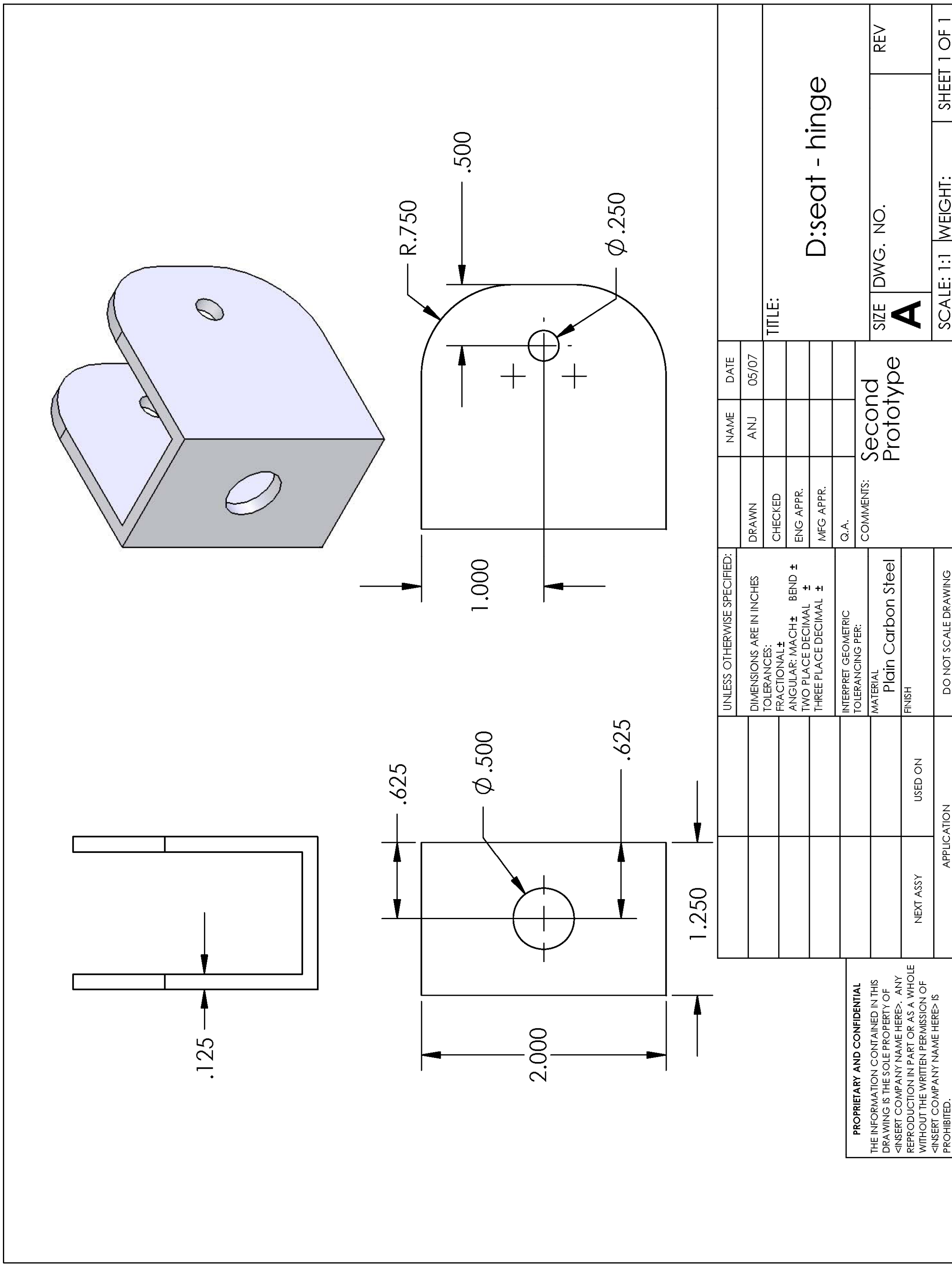
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TOLERANCES:
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
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ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:seat - hinge
SIZE
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DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
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PROPRIETARY AND CONFIDENTIAL
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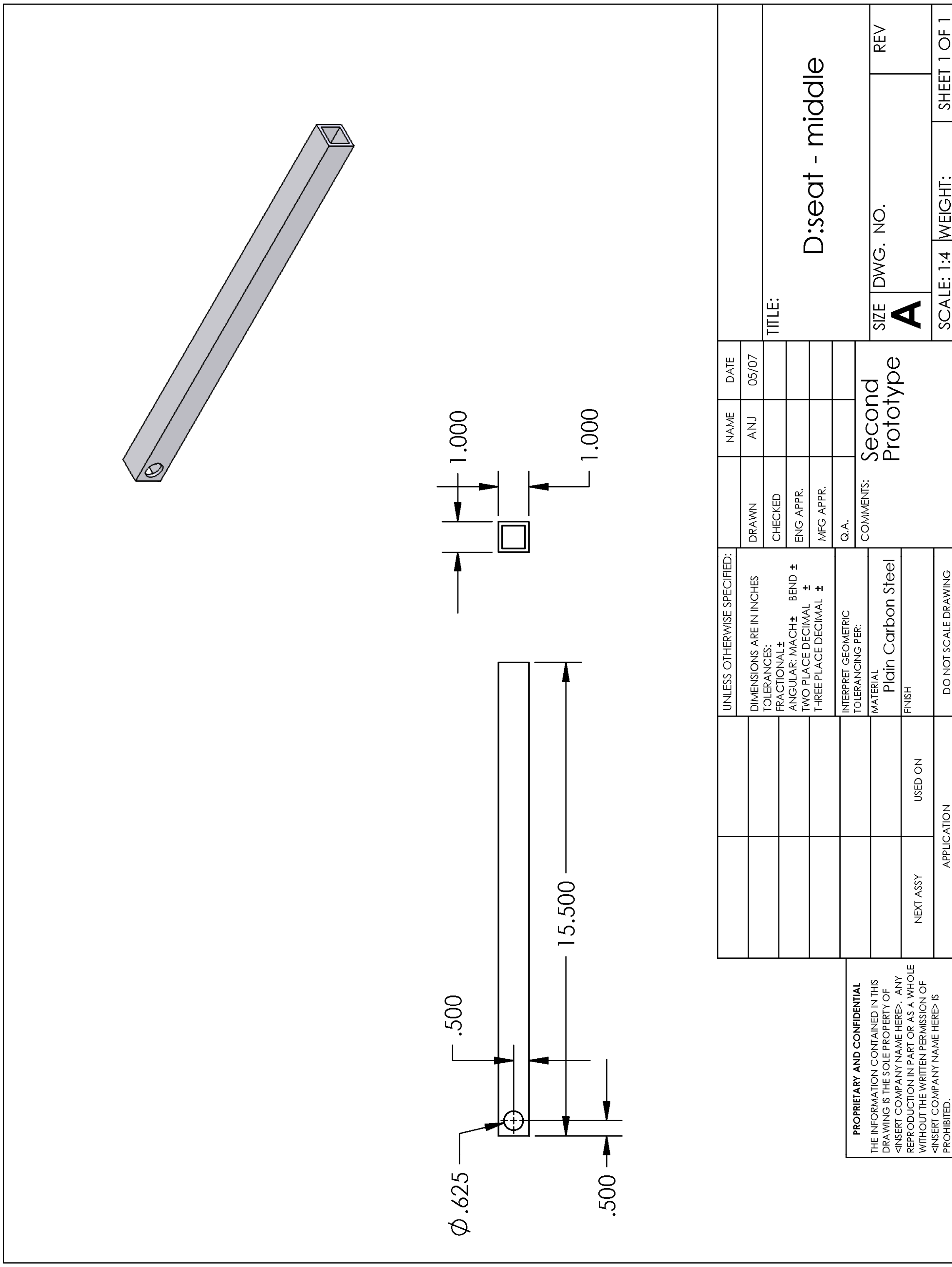
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THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
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APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:seat - middle
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DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
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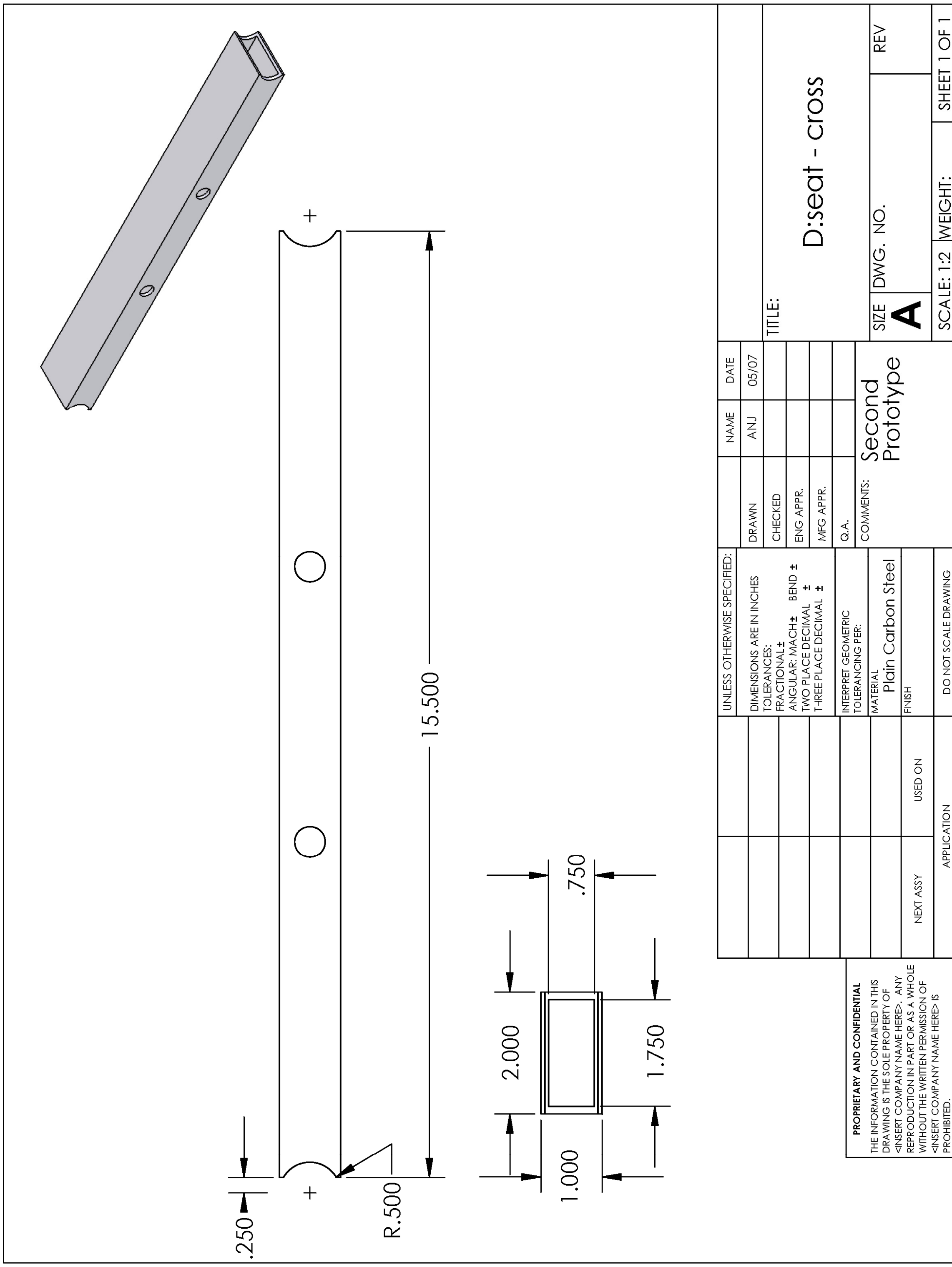
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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
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DWG. NO.
REV
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WEIGHT:
SHEET 1 OF 1
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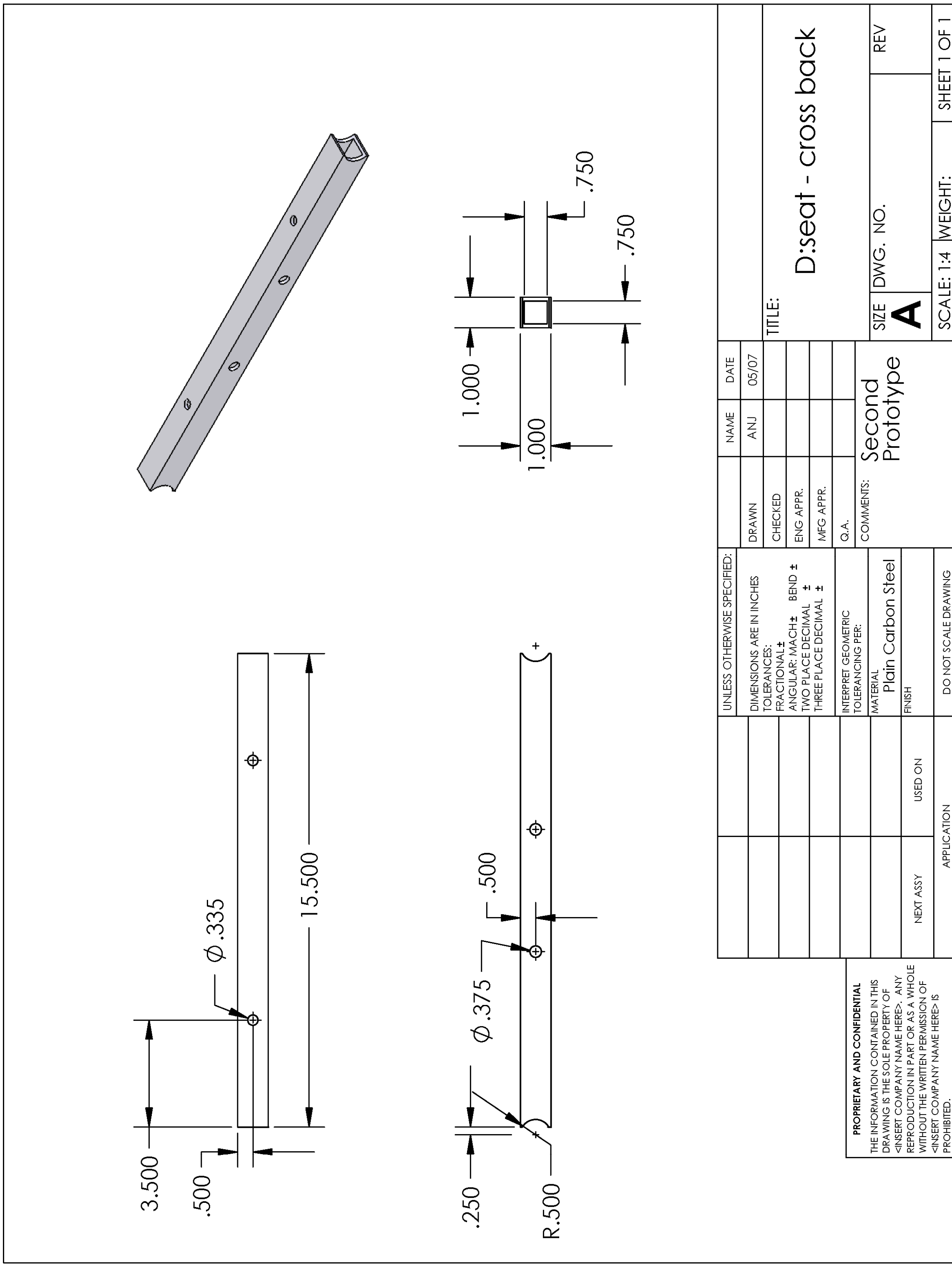
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NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:seat - cross back
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DWG. NO.
REV
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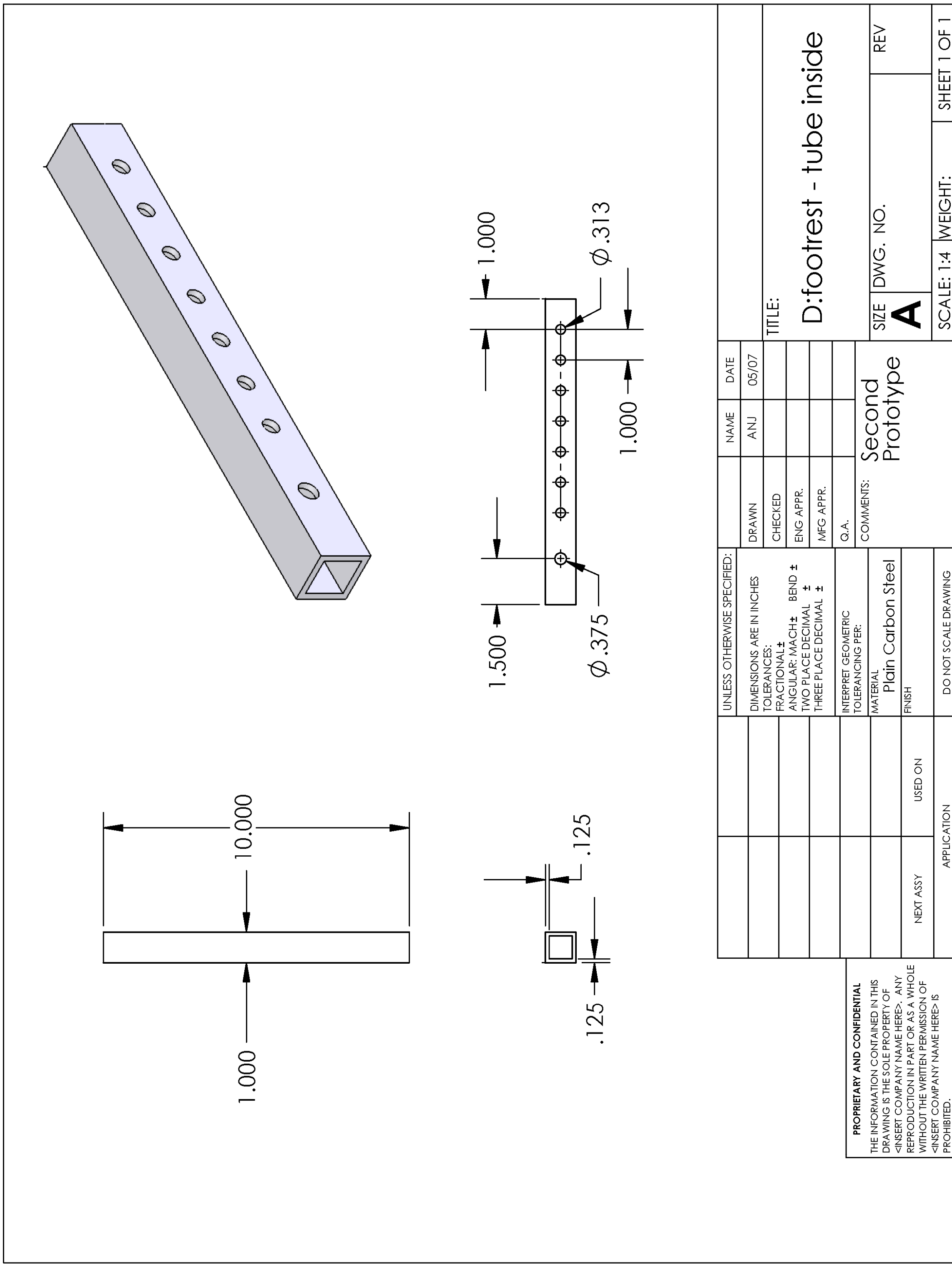
4
3
2
1



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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:footrest - tube inside
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
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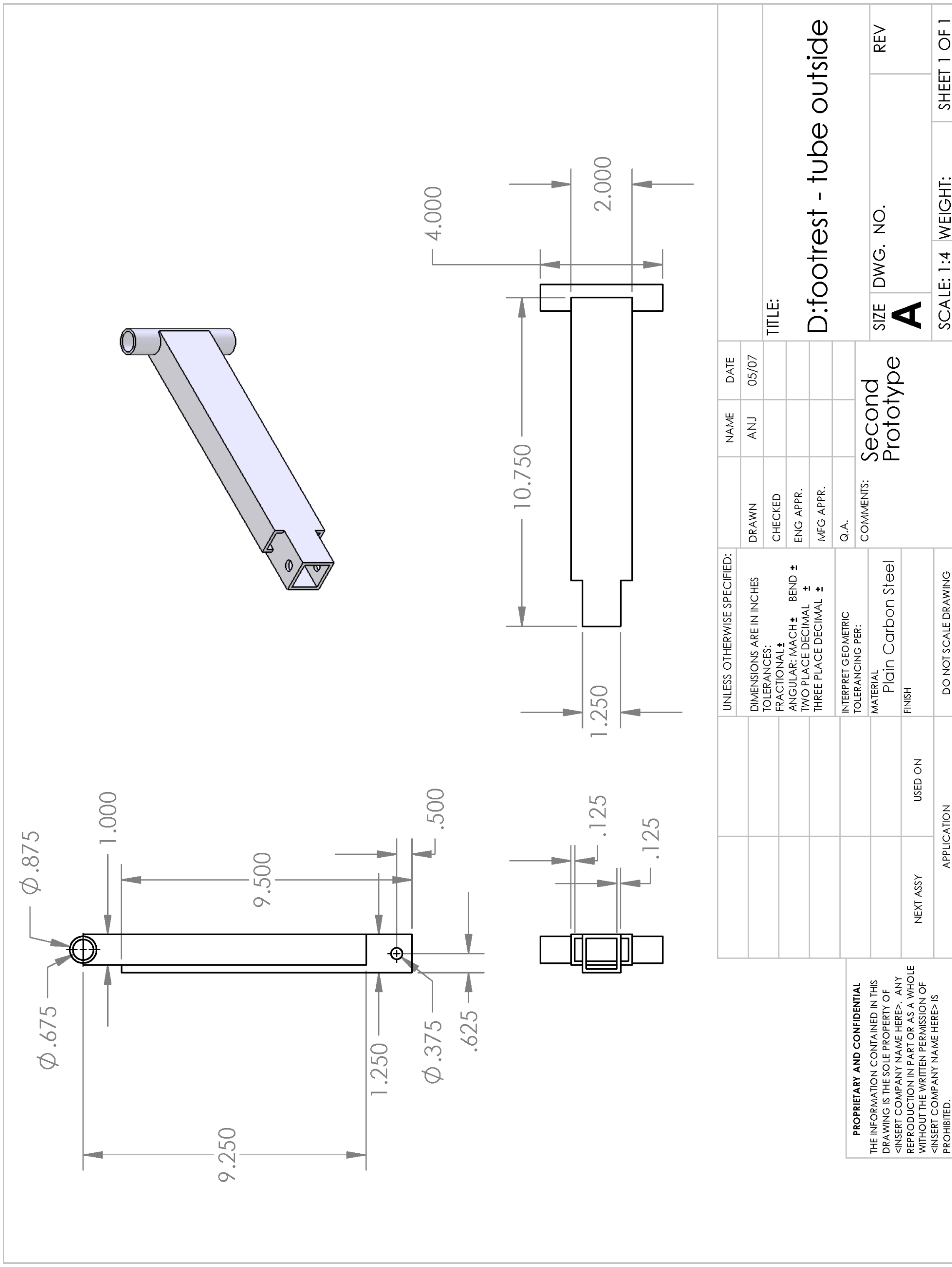
5
4
3
2
1



Ø.875
1.000
Ø.675
9.500
.500
1.250
Ø.375
.625
9.250
.125
.125
1.250
10.750
4.000
2.000
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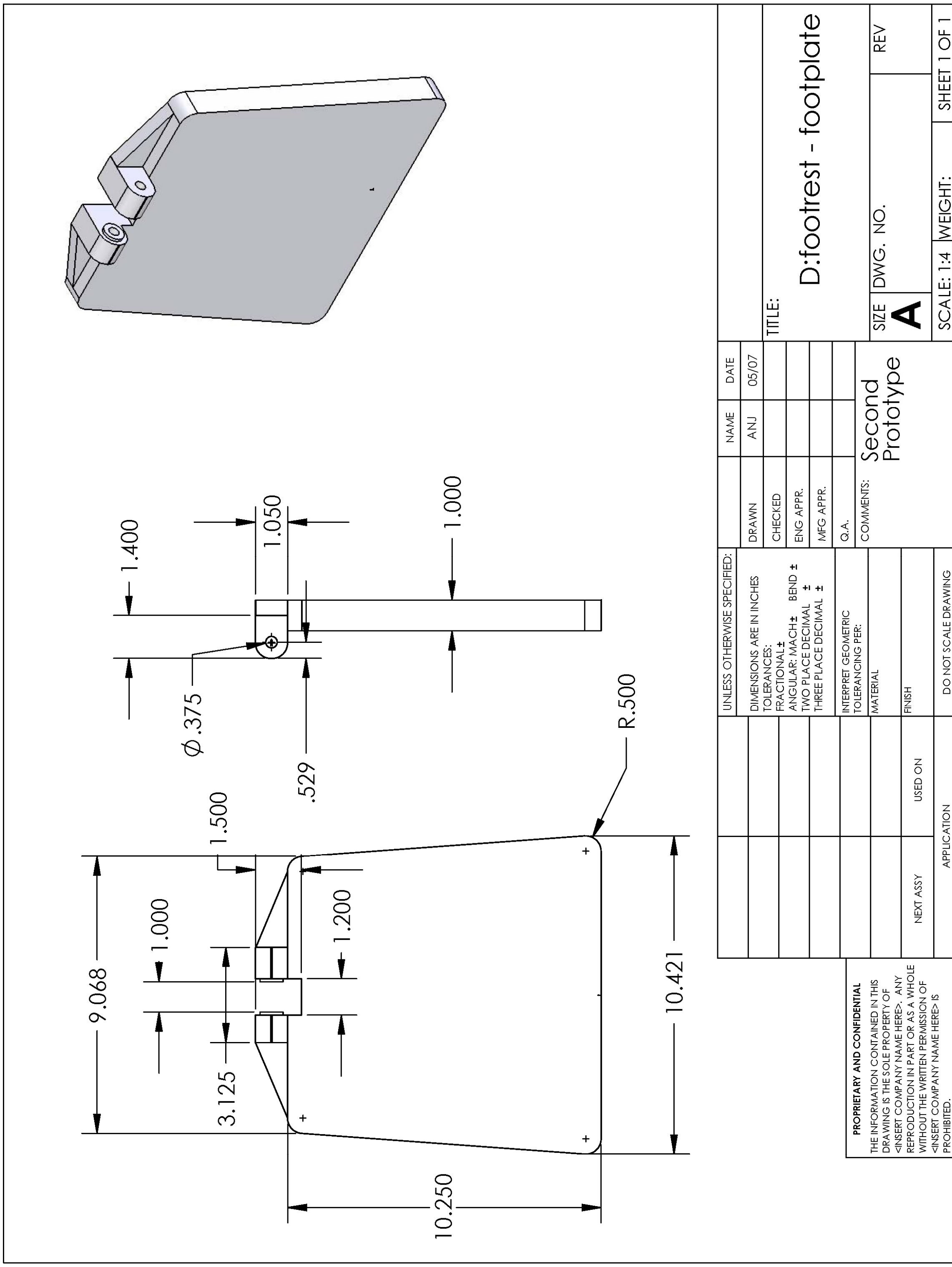
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:footrest - tube outside
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
1
2
3
4
5


9.068
3.125
1.000
1.500
1.200
10.421
10.250
R.500
.529
Ø.375
1.400
1.050
1.000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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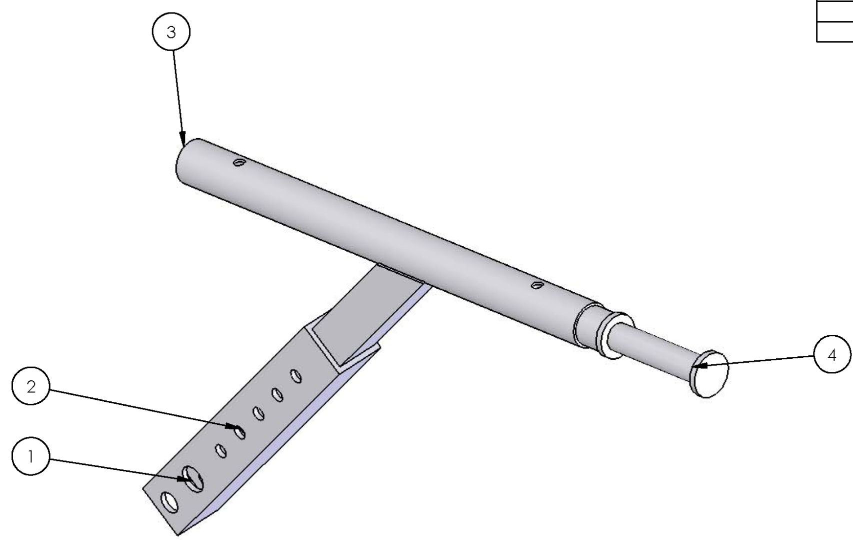
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:footrest - footplate
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1

B.3 ARM REST

The arm-rest is retractable and extendable. The armrest pivots about cross-piece on the seat-frame, and uses a small rubber bumper as a ‘stop’ to keep the arm rest at a horizontal location with respect to the seat-bottom. Height-adjustment is achieved using a telescoping tube system with a quick-release pin. Two pins extend from the end of the arm-rest tube to support the tiller system. One of the pins acts as a pivot, and the other pin acts as a stop; each pin can be telescoped out of the arm-rest tubes to adjust the fore-aft position of the tiller.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	arm rest - outside		1
2	arm rest - inside		1
3	arm rest - horizontal		1
4	tiller - hinge		1

PROPRIETARY AND CONFIDENTIAL

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

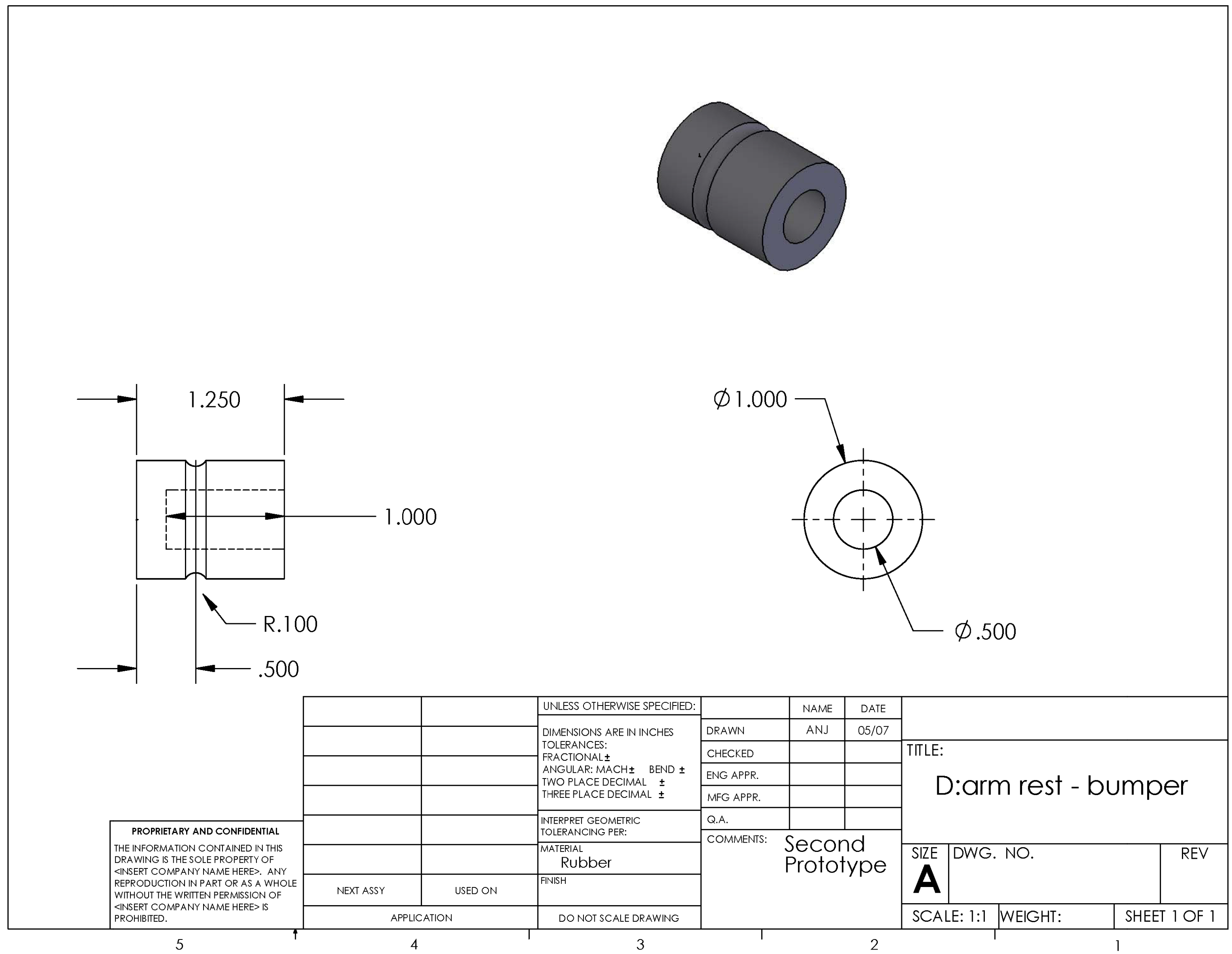
COMMENTS:

TITLE:

Arm Rest Assembly

SIZE **B** | DWG. NO. | REV

SCALE: 1:8 | WEIGHT: | SHEET 4 OF 10


1.250
1.000
R.100
.500
Ø1.000
Ø.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Rubber
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:arm rest - bumper
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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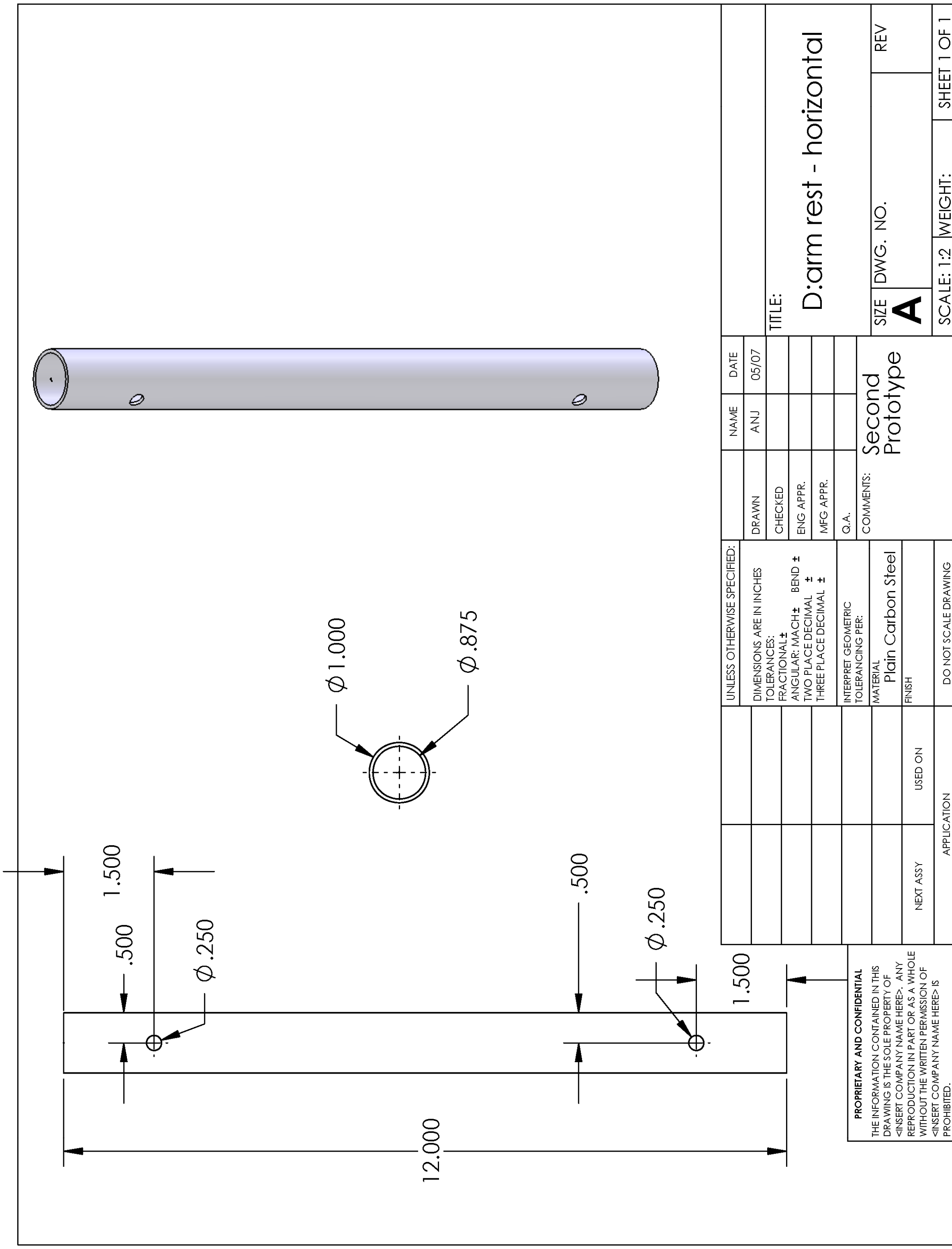
5
4
3
2
1


12.000
1.500
.500
Ø.250
.500
Ø.250
1.500
Ø1.000
Ø.875
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:arm rest - horizontal
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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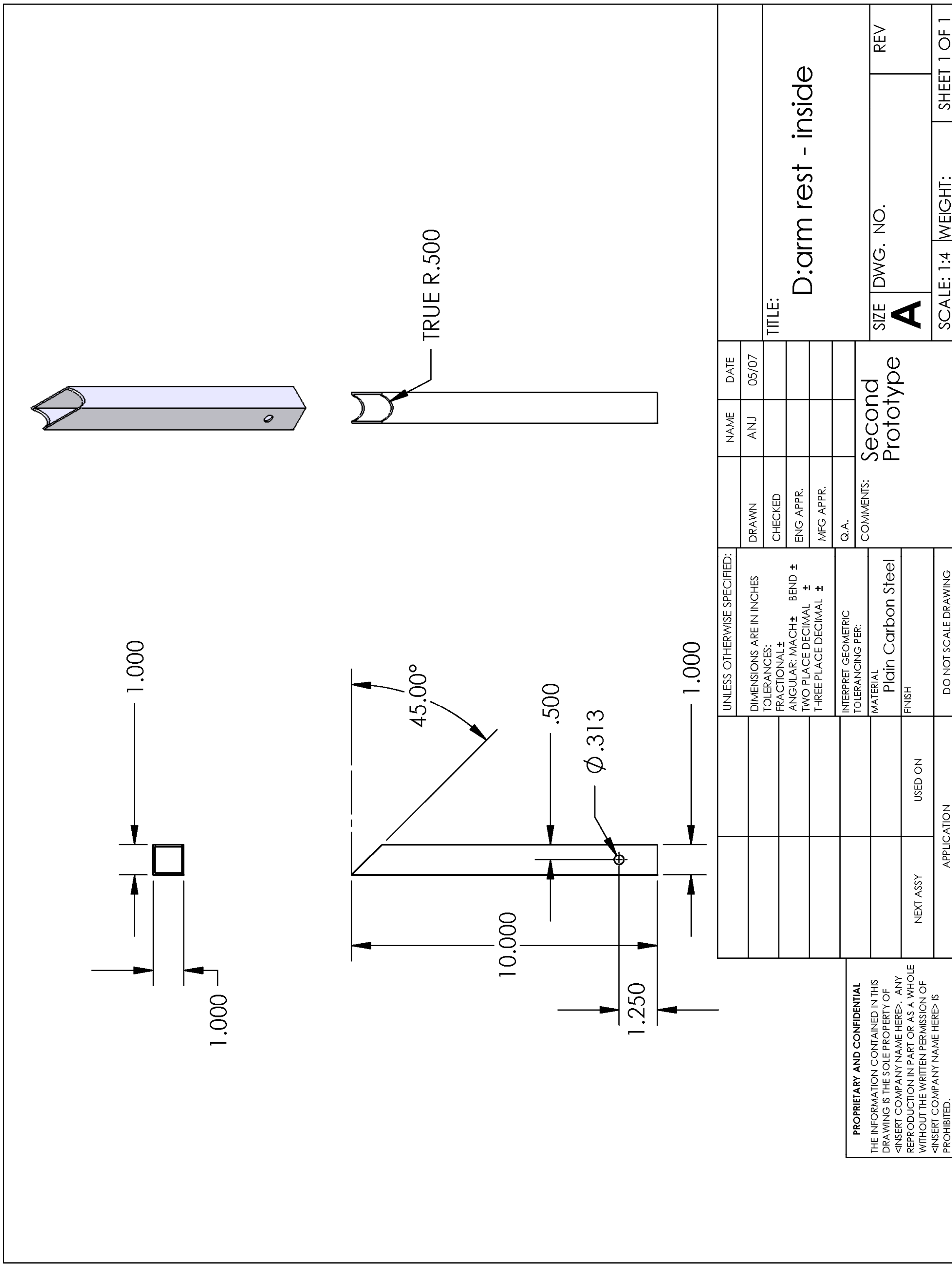
1.000
1.000
45.00°
.500
Ø.313
1.000
10.000
1.250
TRUE R.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:arm rest - inside
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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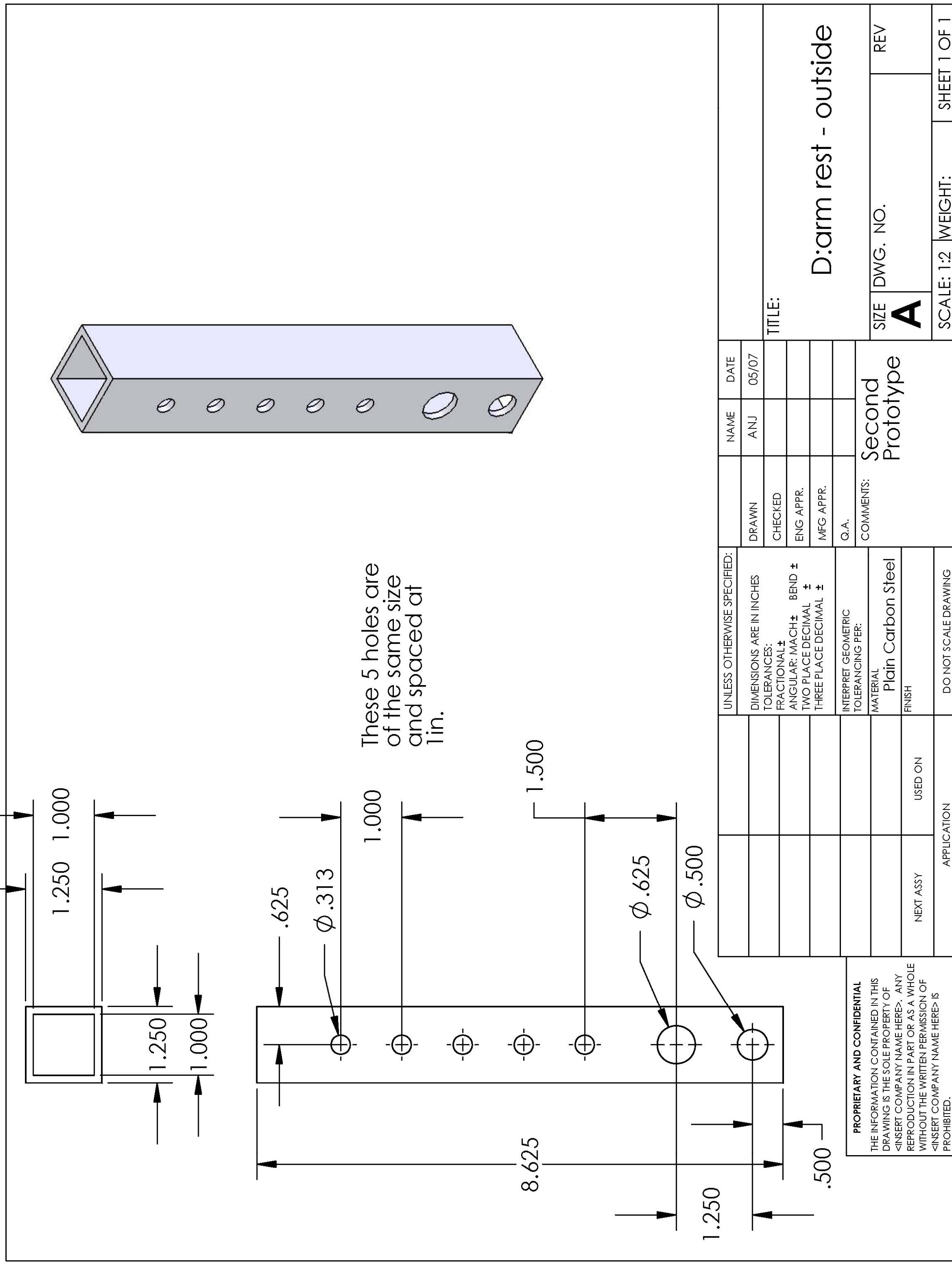
5
4
3
2
1



1.250
1.000
1.250
1.000
.625
Ø.313
1.000
1.500
Ø.625
Ø.500
8.625
.500
1.250
These 5 holes are of the same size and spaced at 1in.
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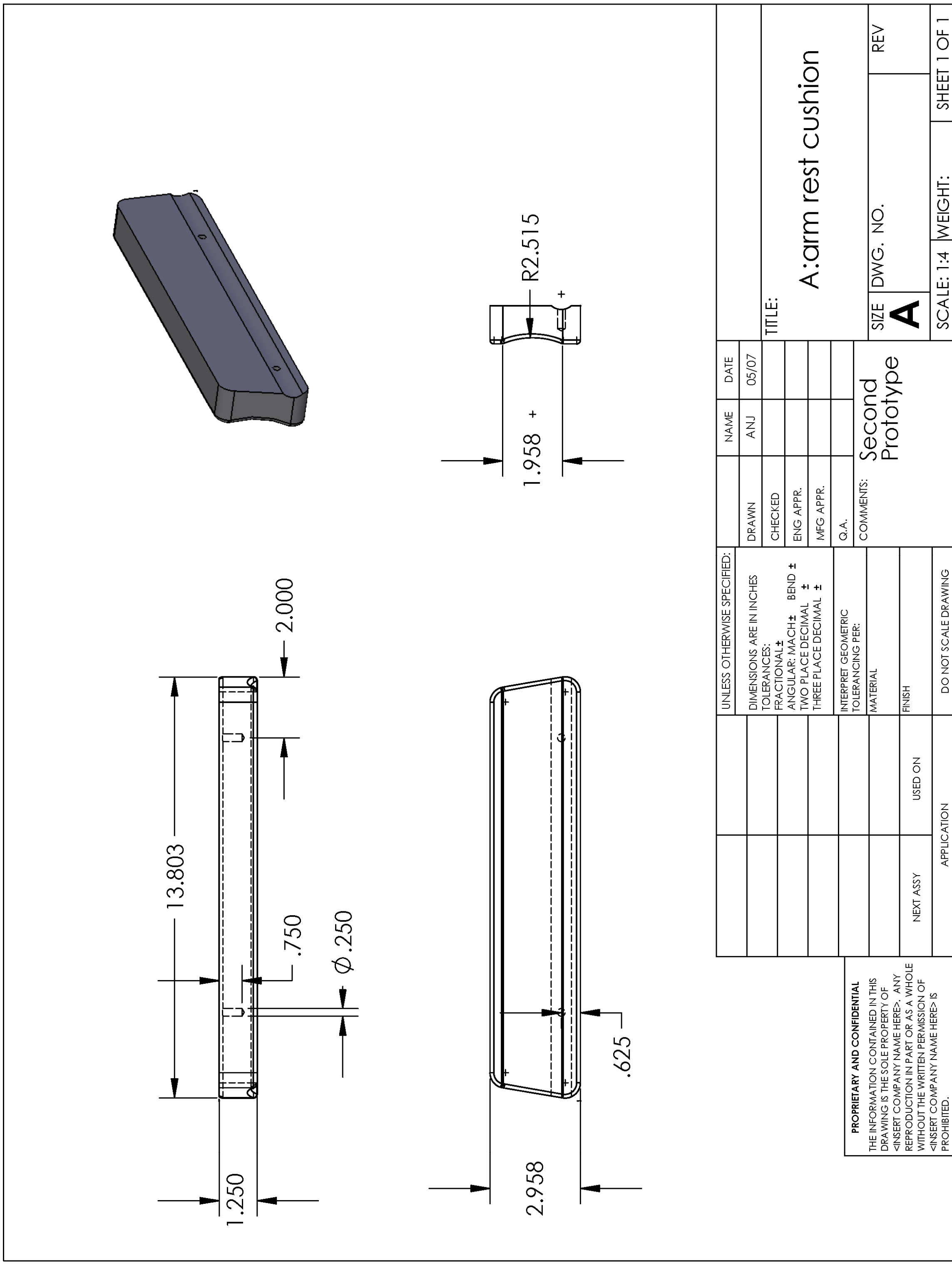
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:arm rest - outside
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



13.803
2.000
.750
Ø.250
1.250
2.958
.625
1.958
R2.515
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:arm rest cushion
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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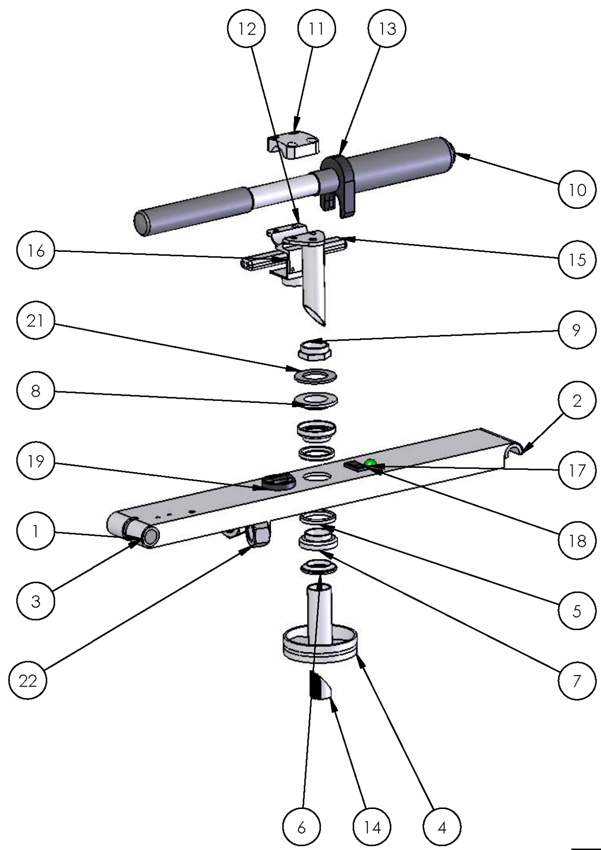
5
4
3
2
1

B.4 TILLER

The tiller system incorporates the steering tiller and the control panel electronics. The tiller mount is constructed from thin-wall rectangular tubing, and has two round tubes (one that is split) welded on each end, which act as the pivot and stop for the swing-away tiller system (see Figure 17). The steering system (handle-bars, head-set system) were adapted from a child's bicycle. Changes included adding a drum onto the bottom of the headset (to accept the turning cables), modifying the head-set to accept a potentiometer) and changing the handle-bar.

The potentiometer controls the forward/rearward and can be actuated either by thumb-extensions screwed to the end of the lever throttle, or through a twist-throttle which interacts with the lever throttle as it is turned. In some cases, as experienced during the user-trials, a combination of the twist and thumb-throttle may prove to be the easiest for some users.

The control-panel electronics are incorporated in to the tiller mount and include a rocker on/off switch, a potentiometer to adjust maximum speed, and an indicator light. Wiring for this control panel exit the tiller mount near the pivot point it makes with the arm-rest pin.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	tiller - mount		1
2	tiller - snap bushing		1
3	tiller - mount bushing		1
4	tiller - cable base		1
5	tiller - bearing		2
6	tiller - bottom bushing		1
7	tiller - horn shaped insert		2
8	tiller - bearing housing top		1
9	tiller - top nut		1
10	tiller - rigid handlebar		1
11	tiller - handlebar bracket top		1
12	tiller - handlebar bracket bottom		1
13	tiller - motorcycle throttle		1
14	tiller - handlebar bracket bottom lock		1
15	tiller - lever throttle		1
16	tiller - potentiometer mount		1
17	electronics - indicator light		1
18	electronics - switch		1
19	electronics - speed potentiometer		1
20	electronics - power plug		1
21	Flat Washer Type B Narrow_Al		1
22	Hex Nut_Al		2

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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

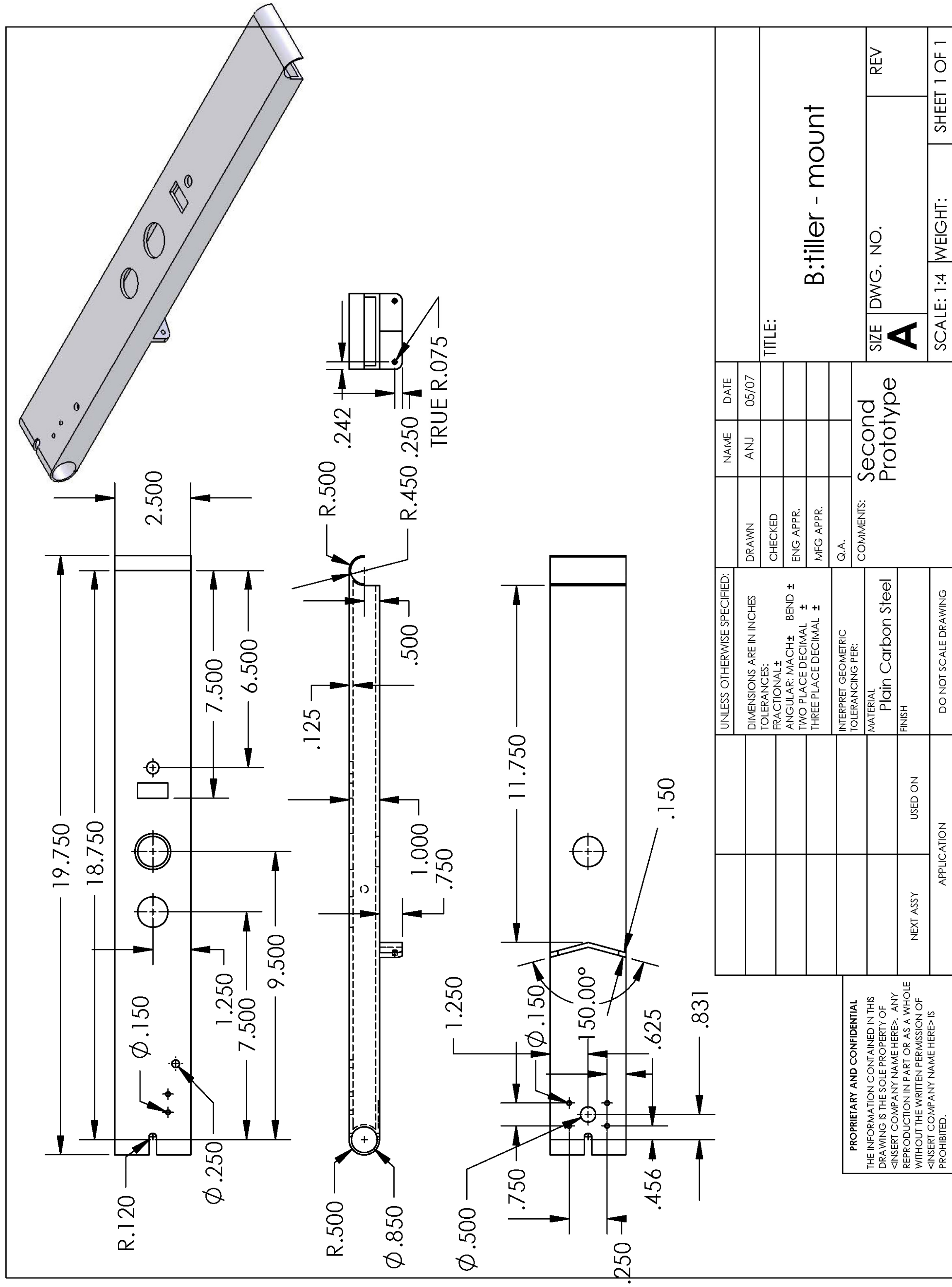
COMMENTS:

TITLE:

Tiller Mount Assembly

SIZE **B** | DWG. NO. | REV

SCALE: 1:8 | WEIGHT: | SHEET 5 OF 10


19.750
18.750
2.500
7.500
6.500
9.500
1.250
7.500
Ø.150
Ø.250
R.120
R.500
Ø.850
.125
.500
1.000
.750
R.500
R.450
.242
.250
TRUE R.075
11.750
.150
150.00°
Ø.150
1.250
.625
.831
.456
.750
Ø.500
1.250
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APPLICATION
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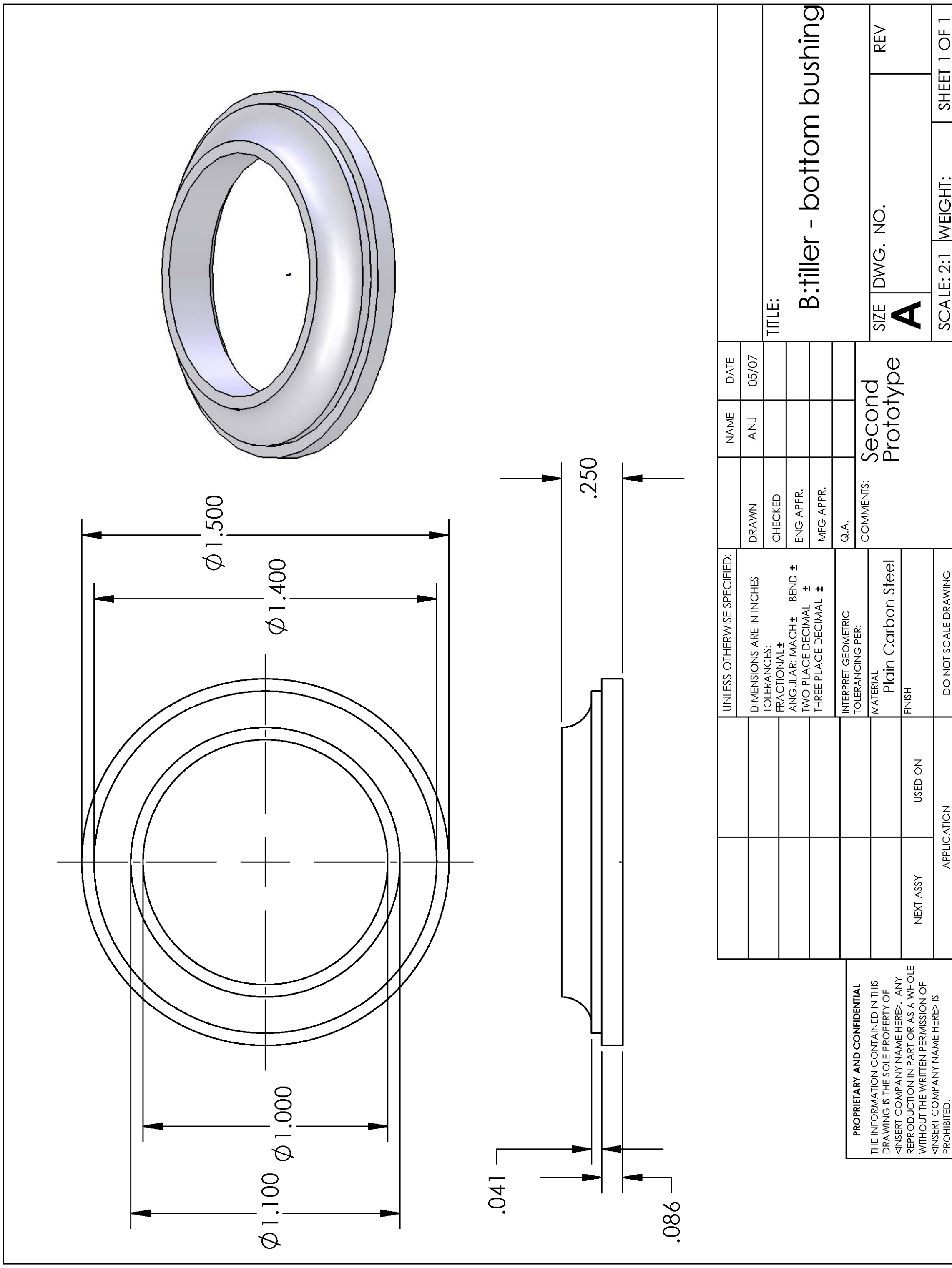
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
B:tiller - mount
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


Ø1.500
Ø1.400
Ø1.000
Ø1.100
.250
.041
.086
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
B:tiller - bottom bushing
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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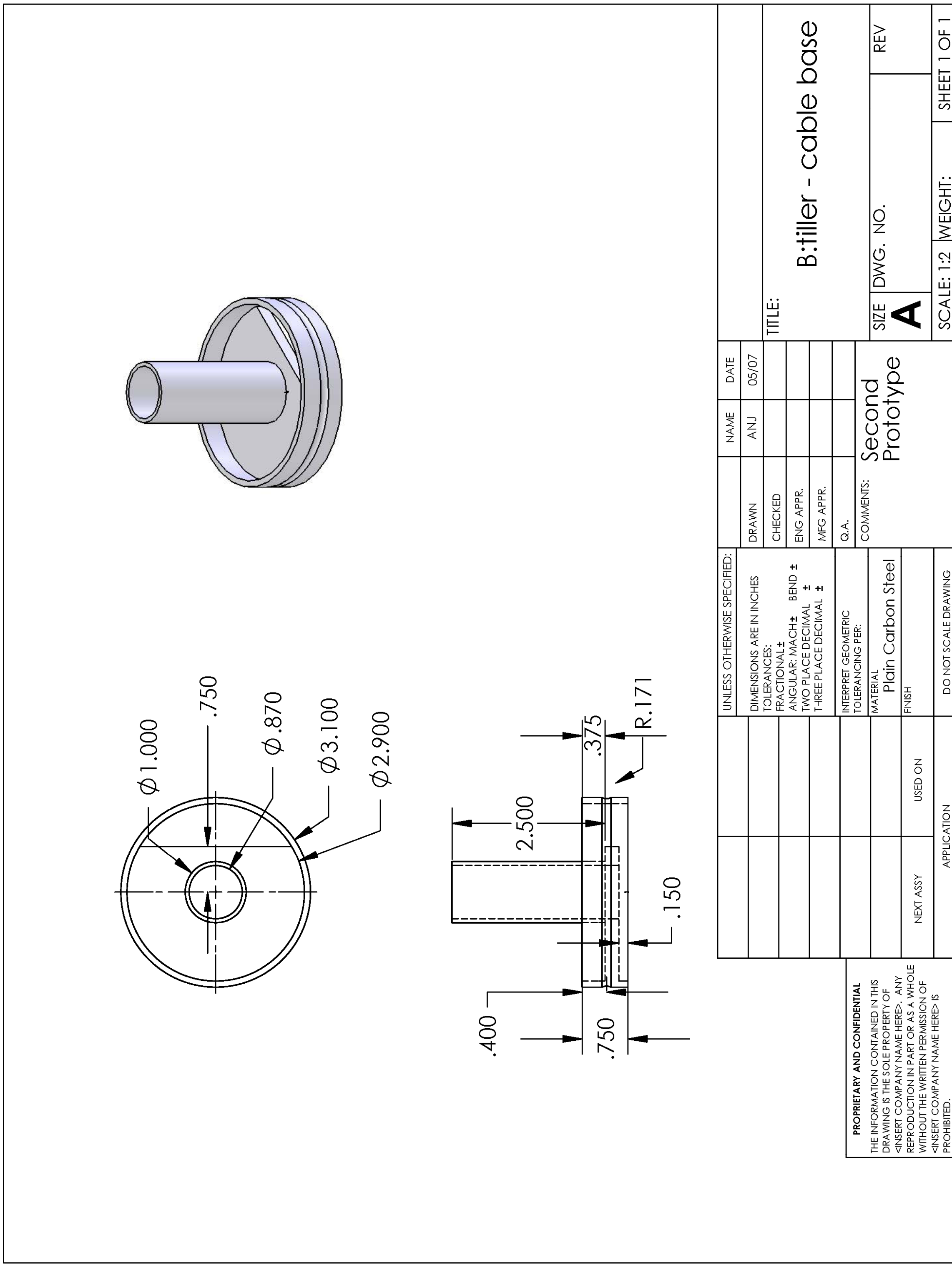
5
4
3
2
1


Ø1.000
.750
Ø.870
Ø3.100
Ø2.900
2.500
.375
R.171
.150
.400
.750
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second
Prototype
TITLE:
B:tiller - cable base
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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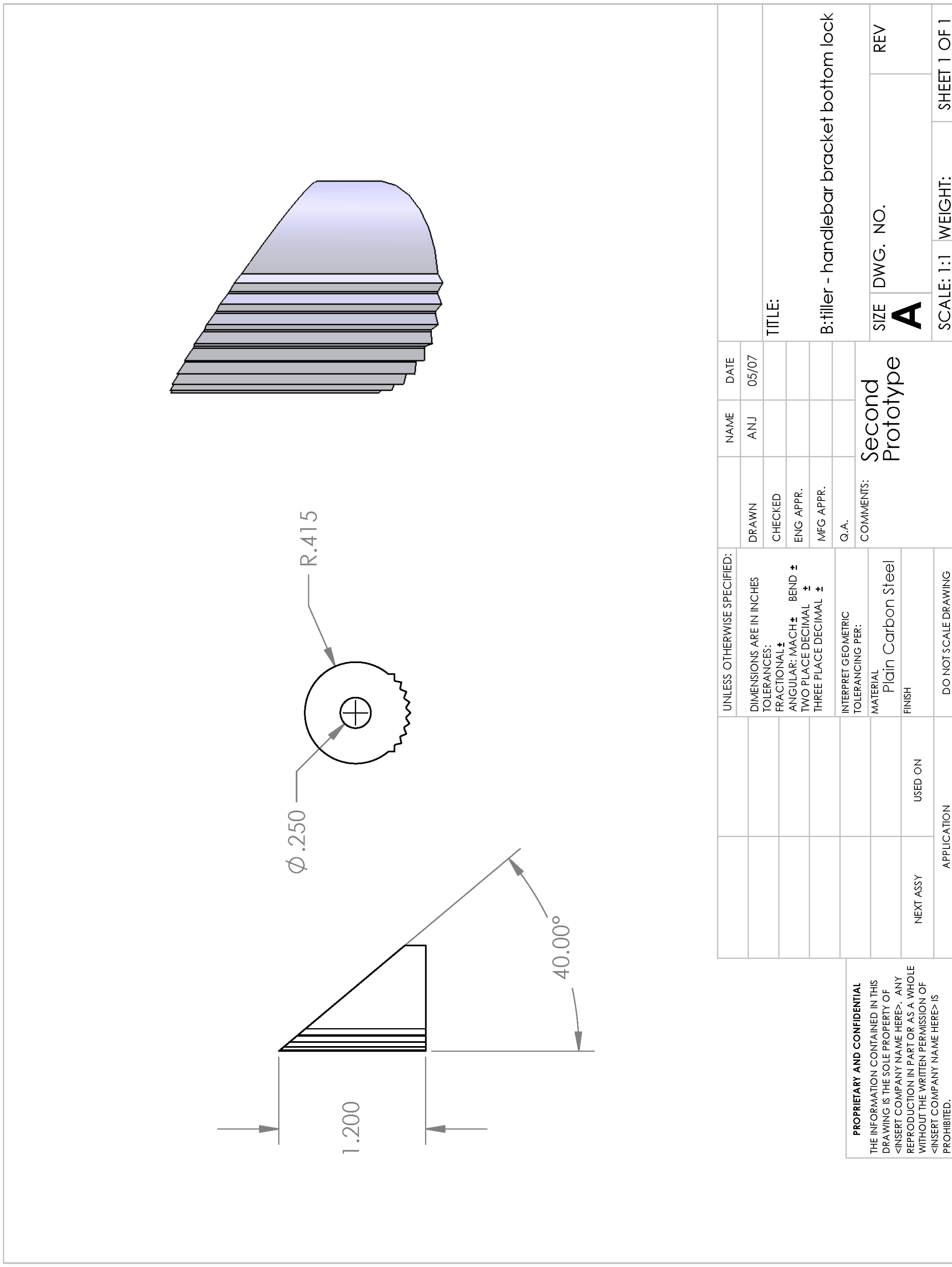
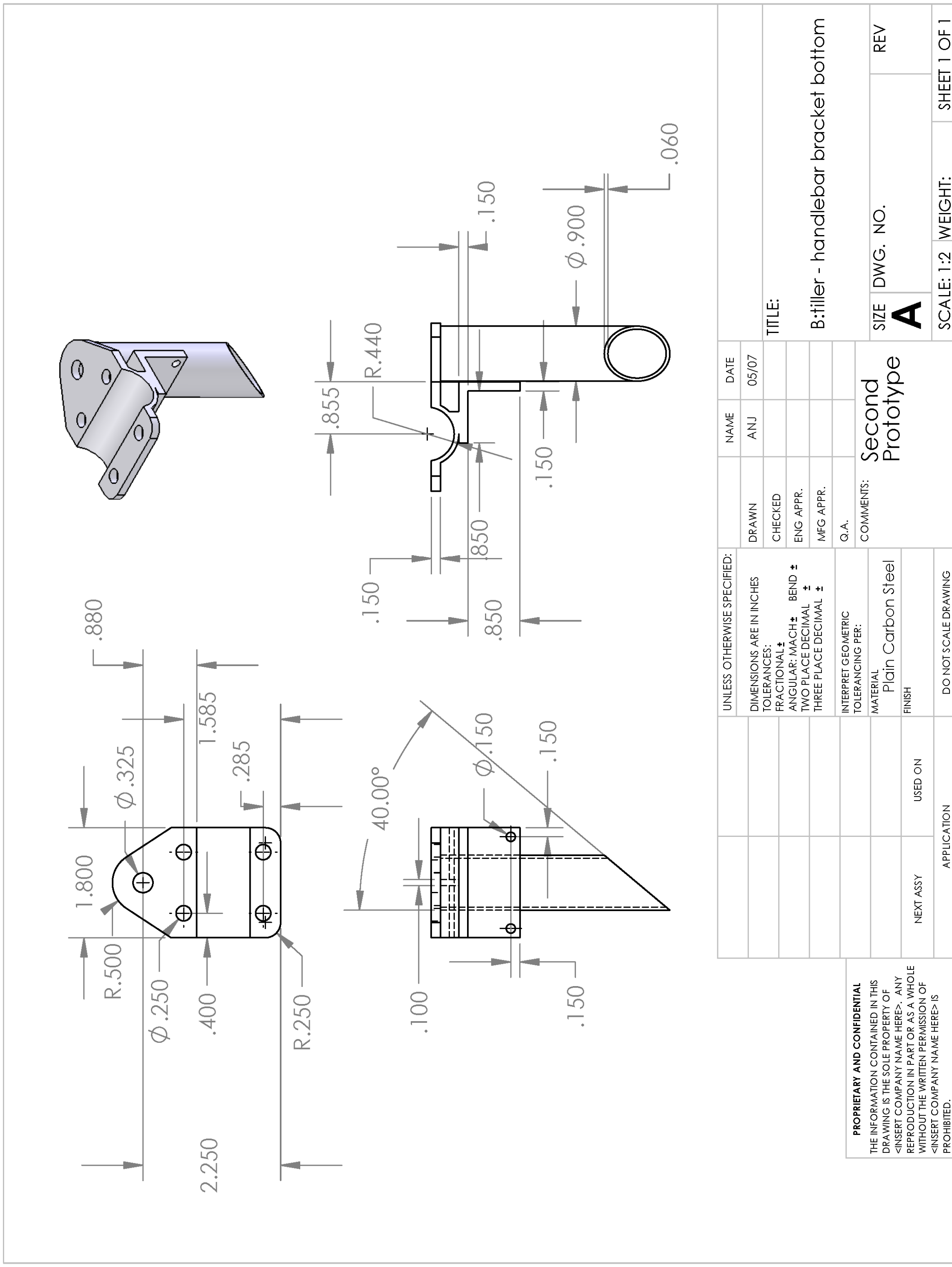
5
4
3
2
1


1.200
40.00°
Ø.250
R.415
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
B:filler - handlebar bracket bottom lock
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


2.250
1.800
R.500
Ø.325
Ø.250
.400
.880
1.585
.285
R.250
40.00°
Ø.150
.150
.100
.150
.150
.850
.850
.150
.855
R.440
Ø.900
.150
.060
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
B:tiller - handlebar bracket bottom
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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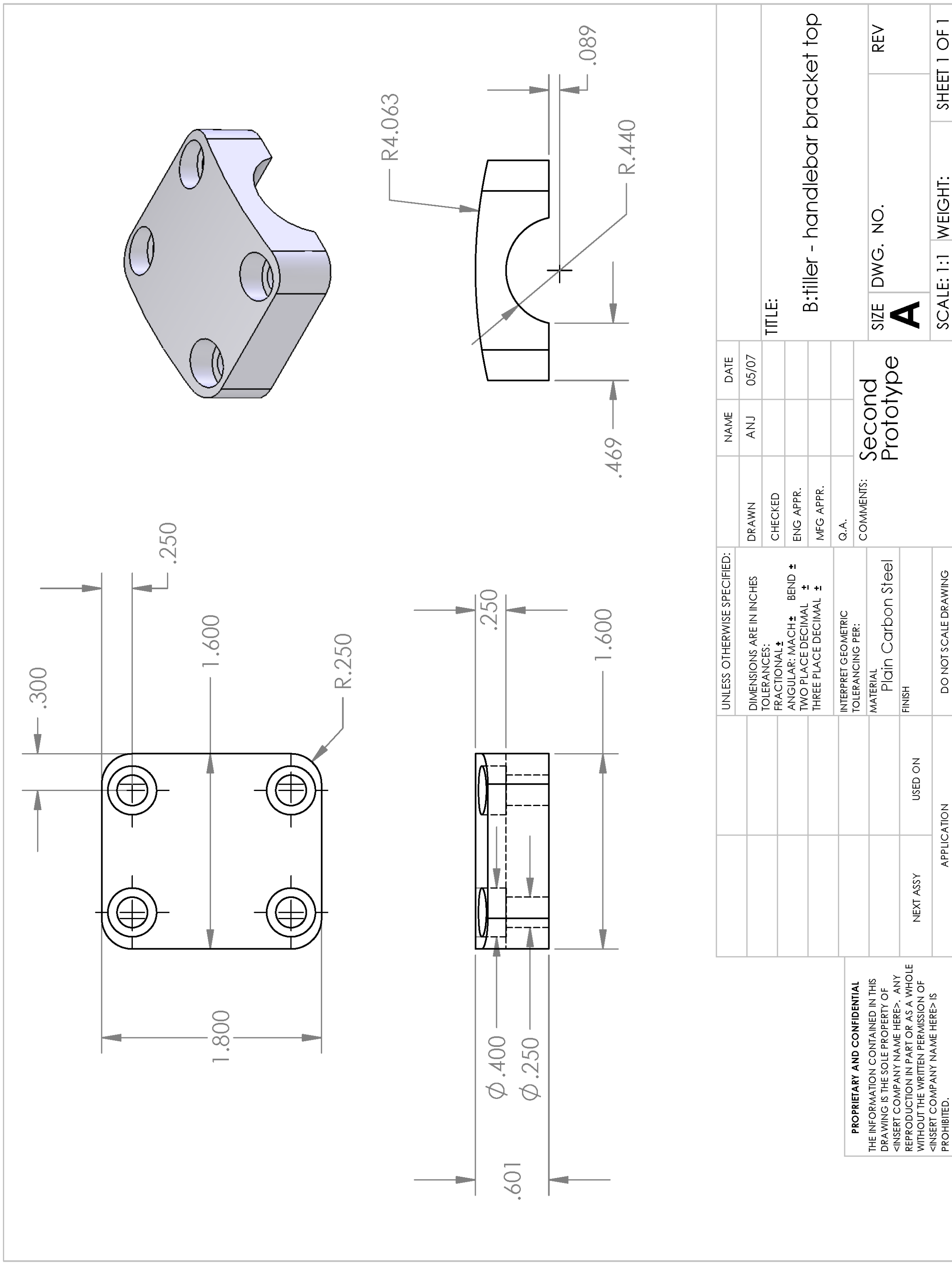
5
4
3
2
1



.300
.250
1.600
R.250
1.800
.250
1.600
Ø.400
Ø.250
.601
R4.063
.089
R.440
.469
PROPRIETARY AND CONFIDENTIAL
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USED ON
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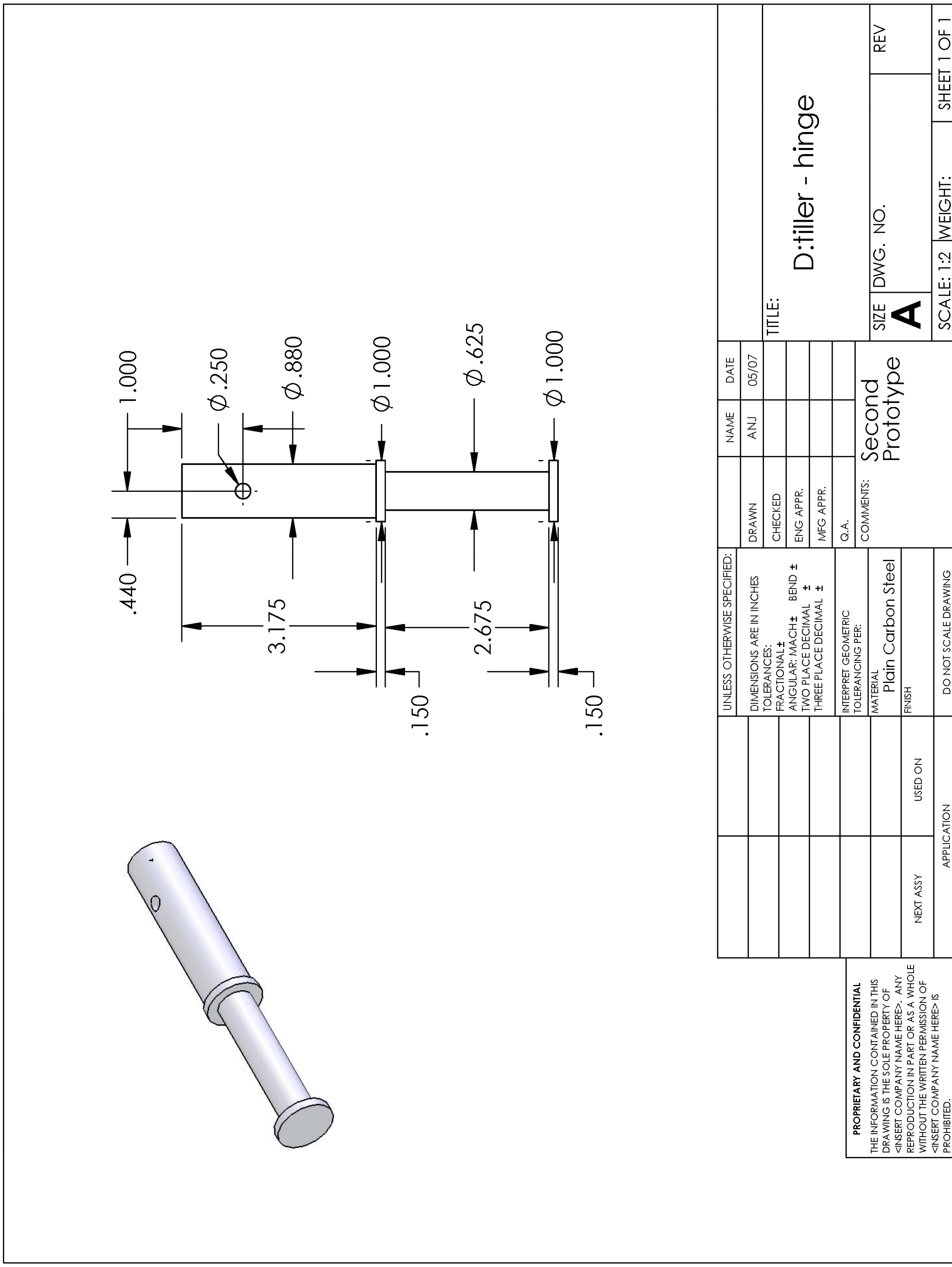
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
B:tiller - handlebar bracket top
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1



1.000
.440
Ø.250
Ø.880
3.175
Ø1.000
Ø.625
2.675
Ø1.000
.150
.150
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:tiller - hinge
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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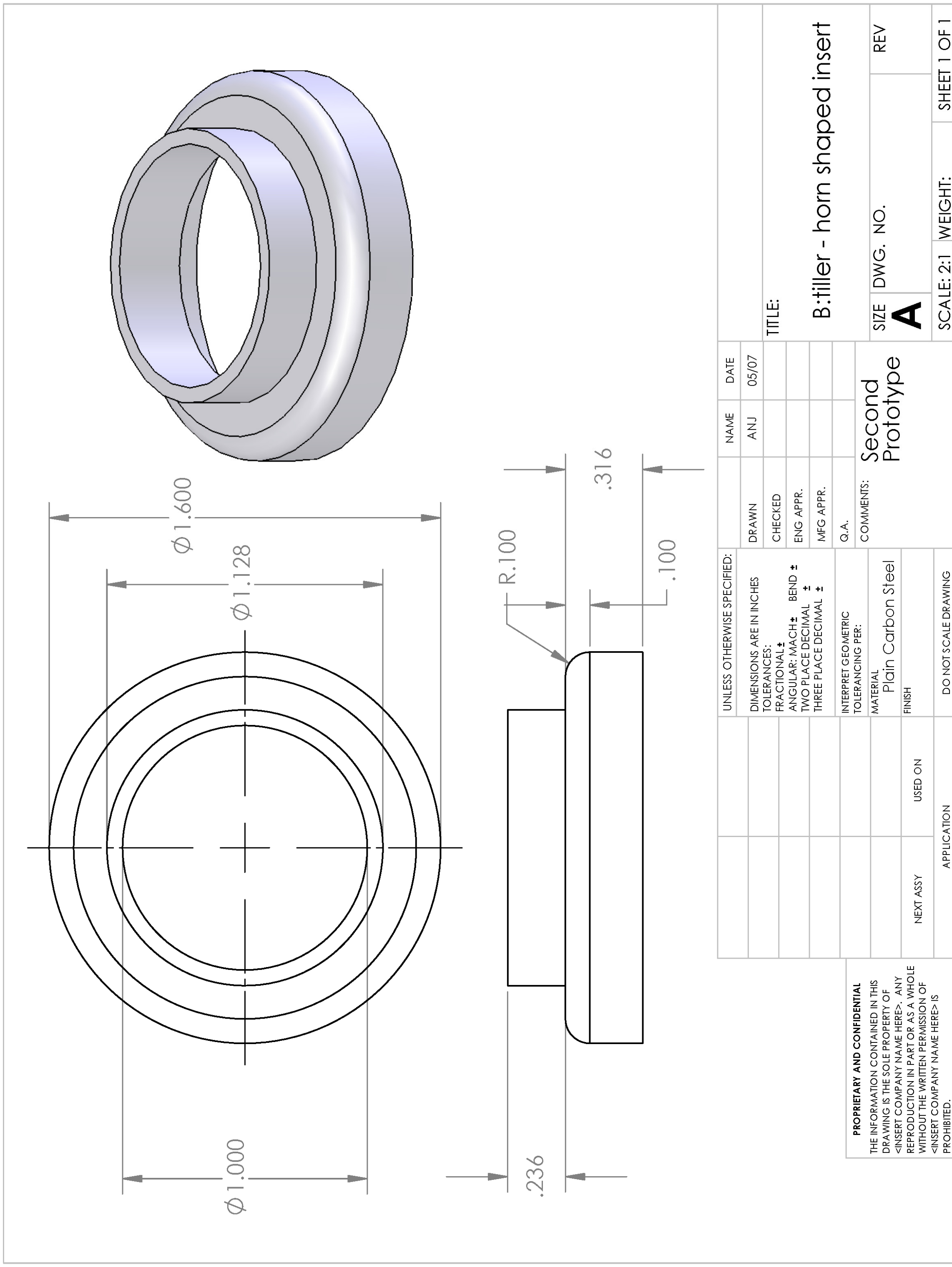
5
4
3
2
1



Ø1.600
Ø1.128
Ø1.000
R.100
.316
.100
.236
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
B:tiller - horn shaped insert
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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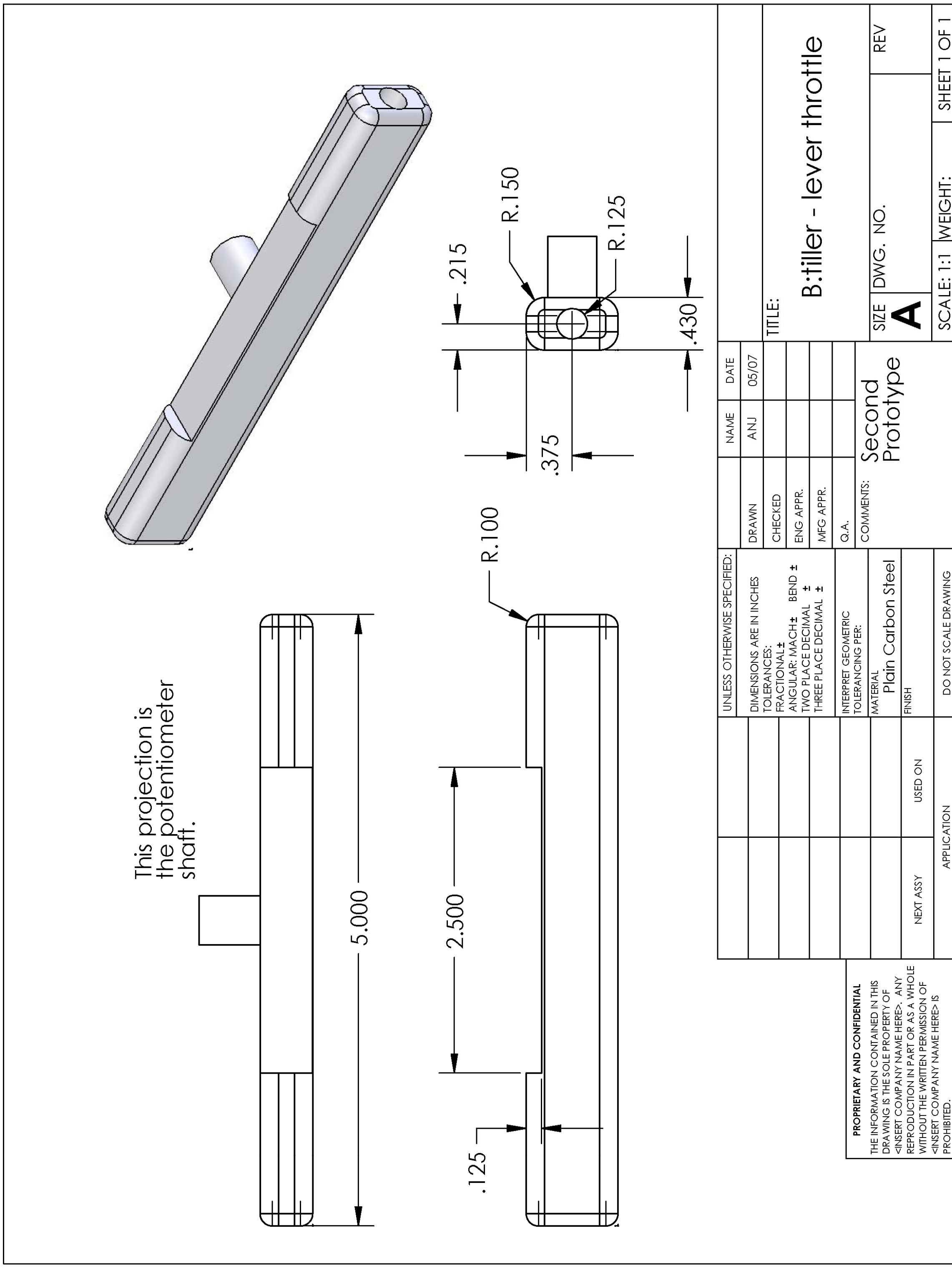
This projection is the potentiometer shaft.
5.000
2.500
.125
R.100
R.150
R.125
.215
.430
.375
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
B:tiller - lever throttle
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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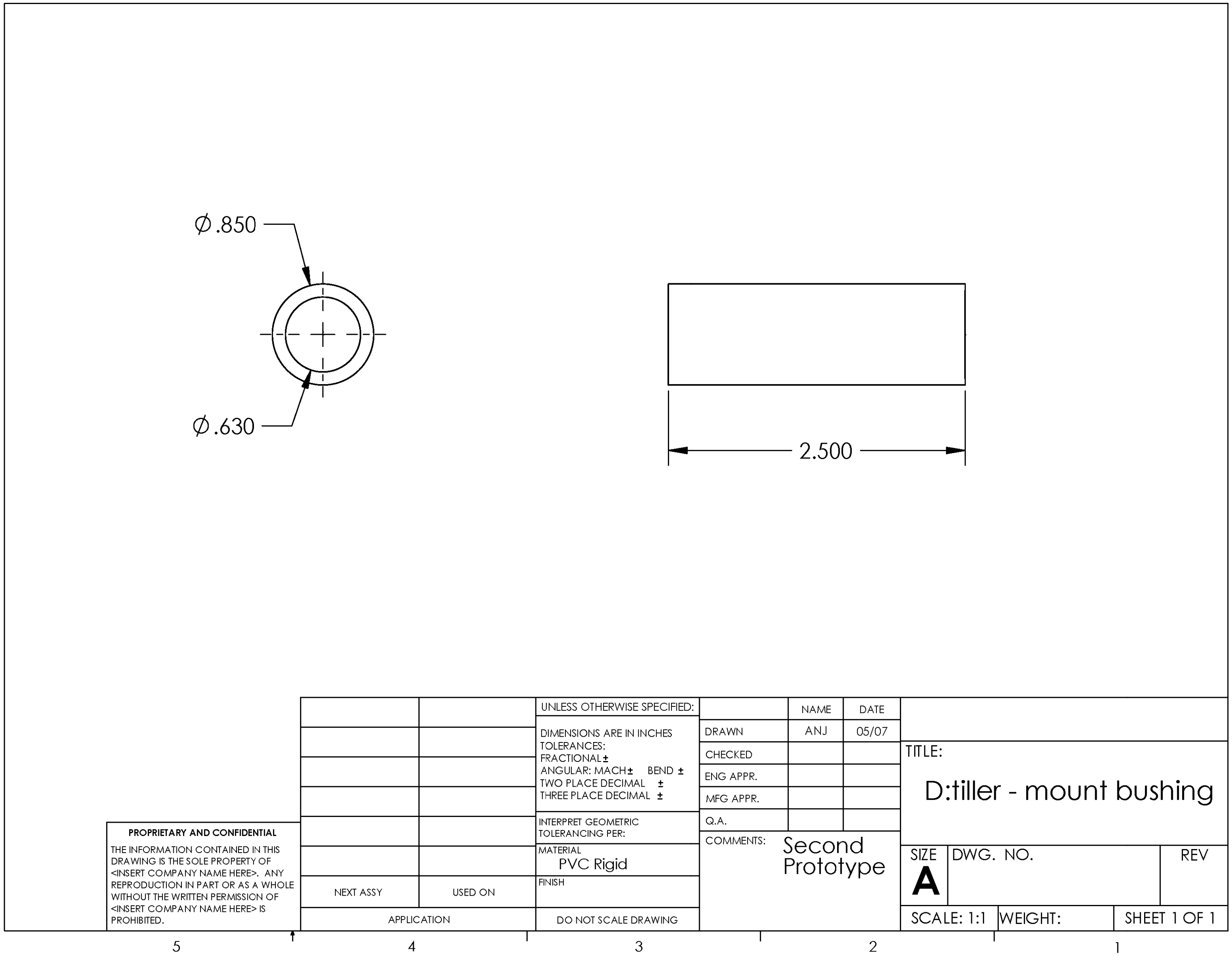
4
3
2
1



∅.850
∅.630
2.500
PROPRIETARY AND CONFIDENTIAL
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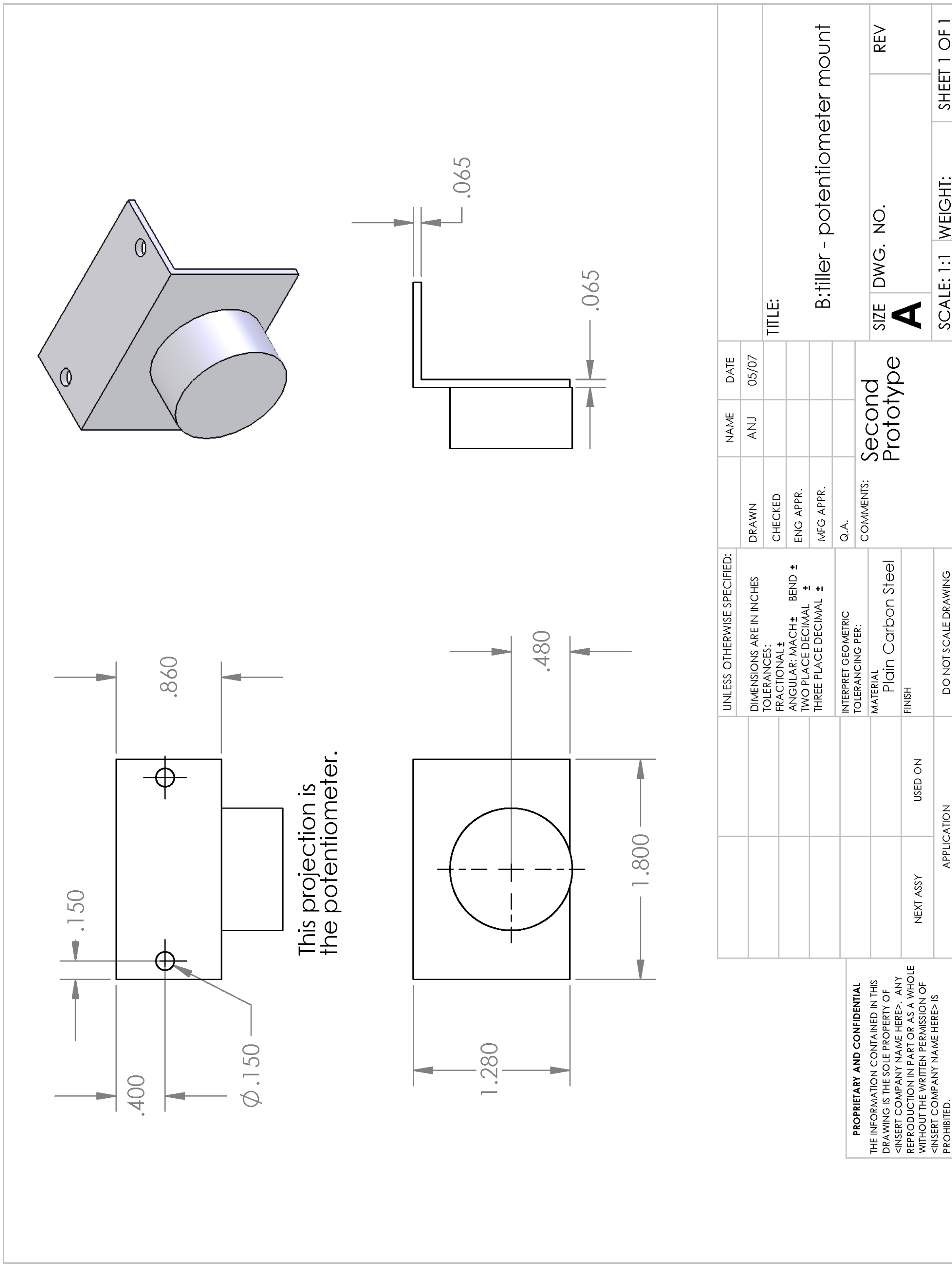
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PVC Rigid
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:tiller - mount bushing
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



.065
.065
.860
.480
.150
This projection is
the potentiometer.
1.800
1.280
.400
Ø.150
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second
Prototype
TITLE:
B:tiller - potentiometer mount
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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4
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2
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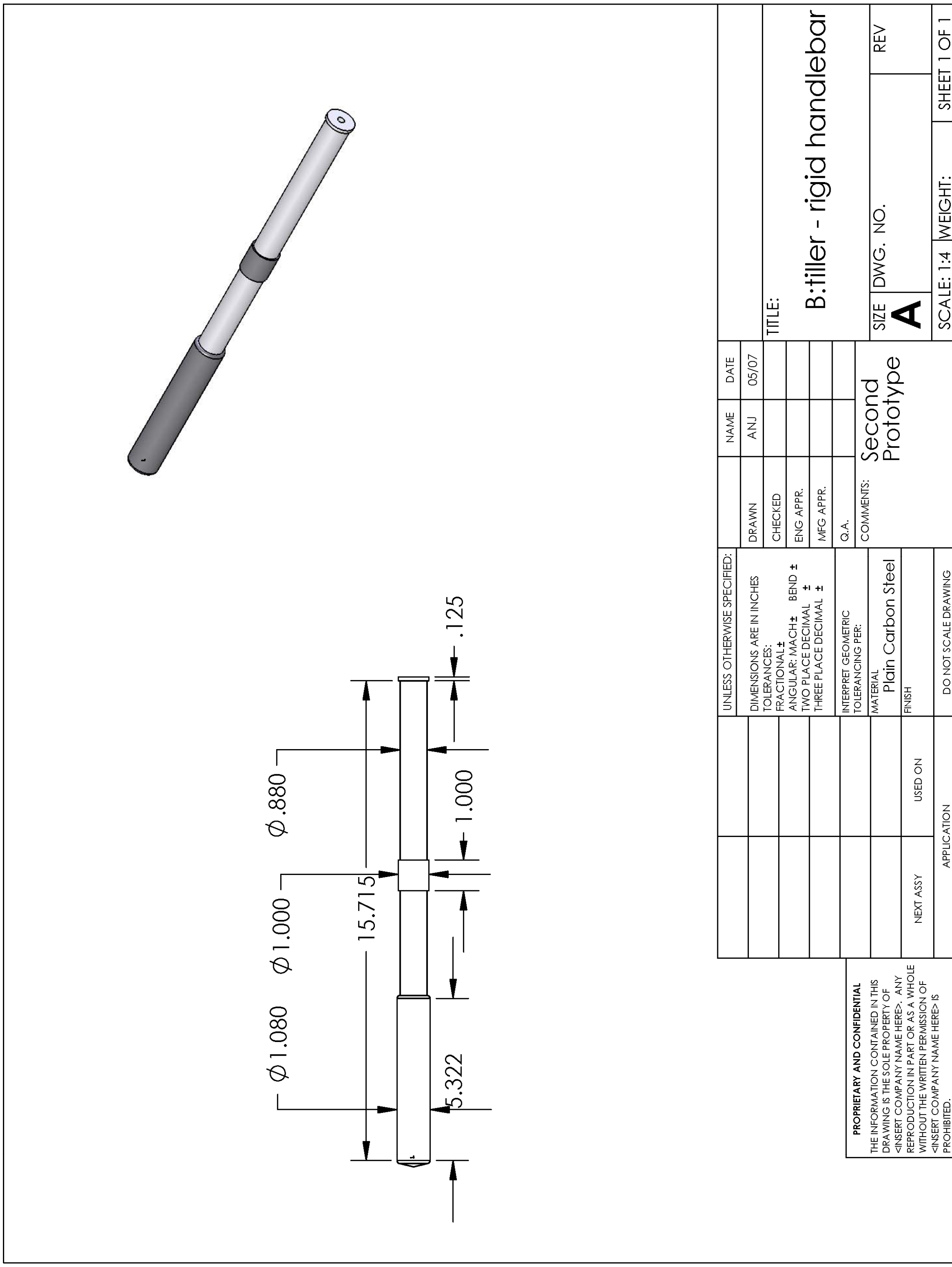

Ø1.080
Ø1.000
Ø.880
15.715
1.000
.125
5.322
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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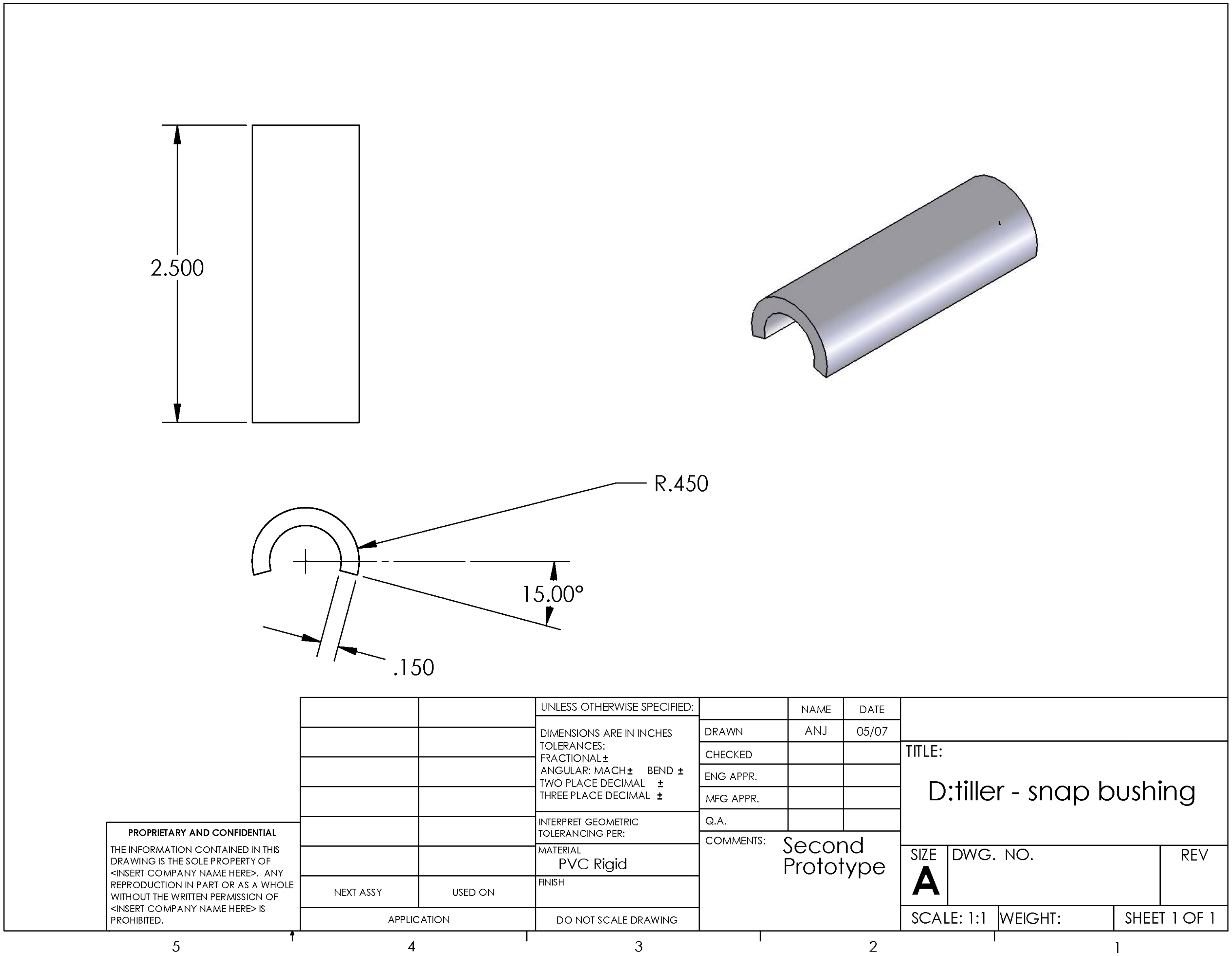
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
B:tiller - rigid handlebar
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


2.500
R.450
15.00°
.150
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PVC Rigid
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
D:tiller - snap bushing
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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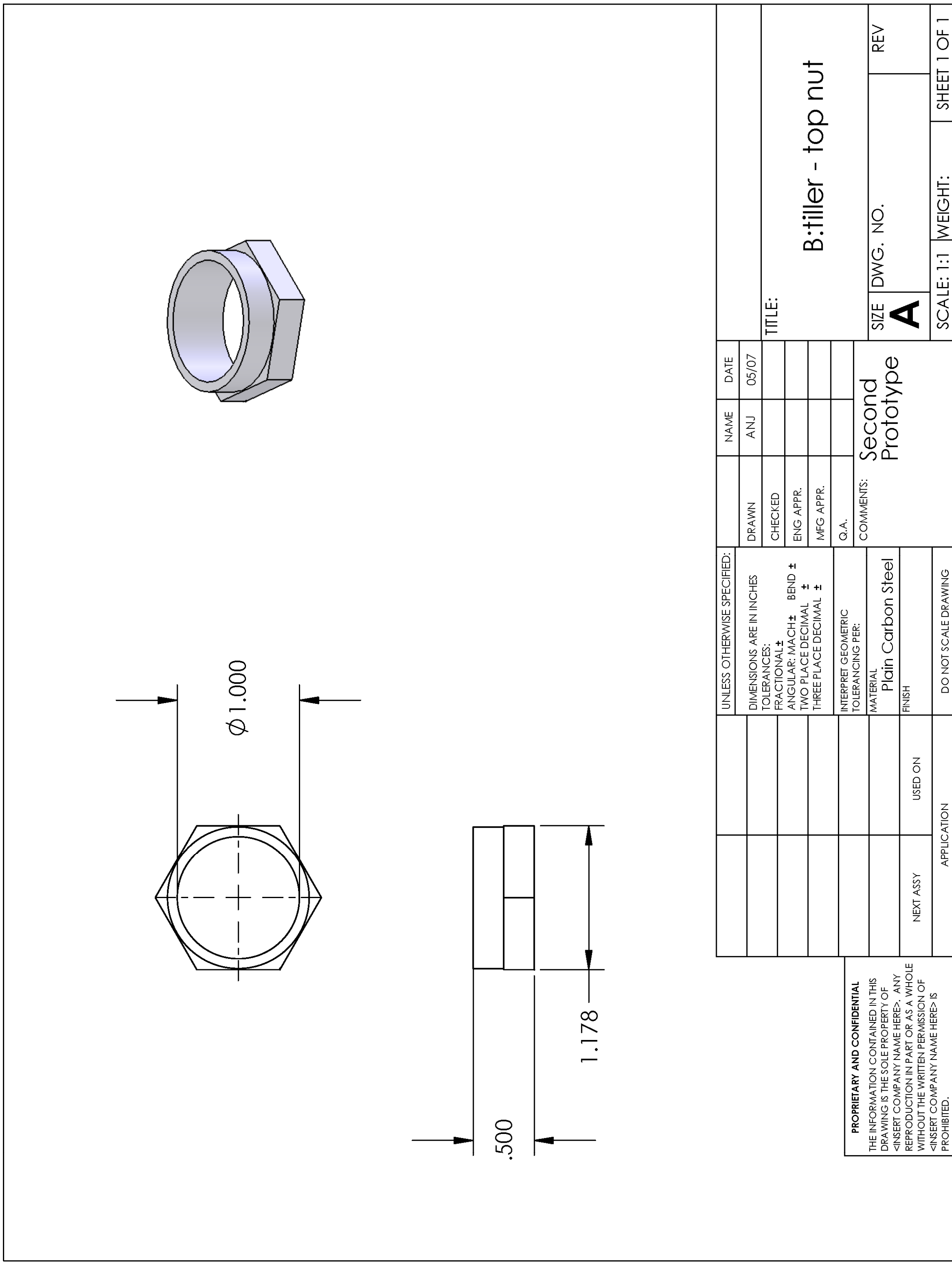
5
4
3
2
1



Ø1.000
1.178
.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second
Prototype
TITLE:
B:tiller - top nut
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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4
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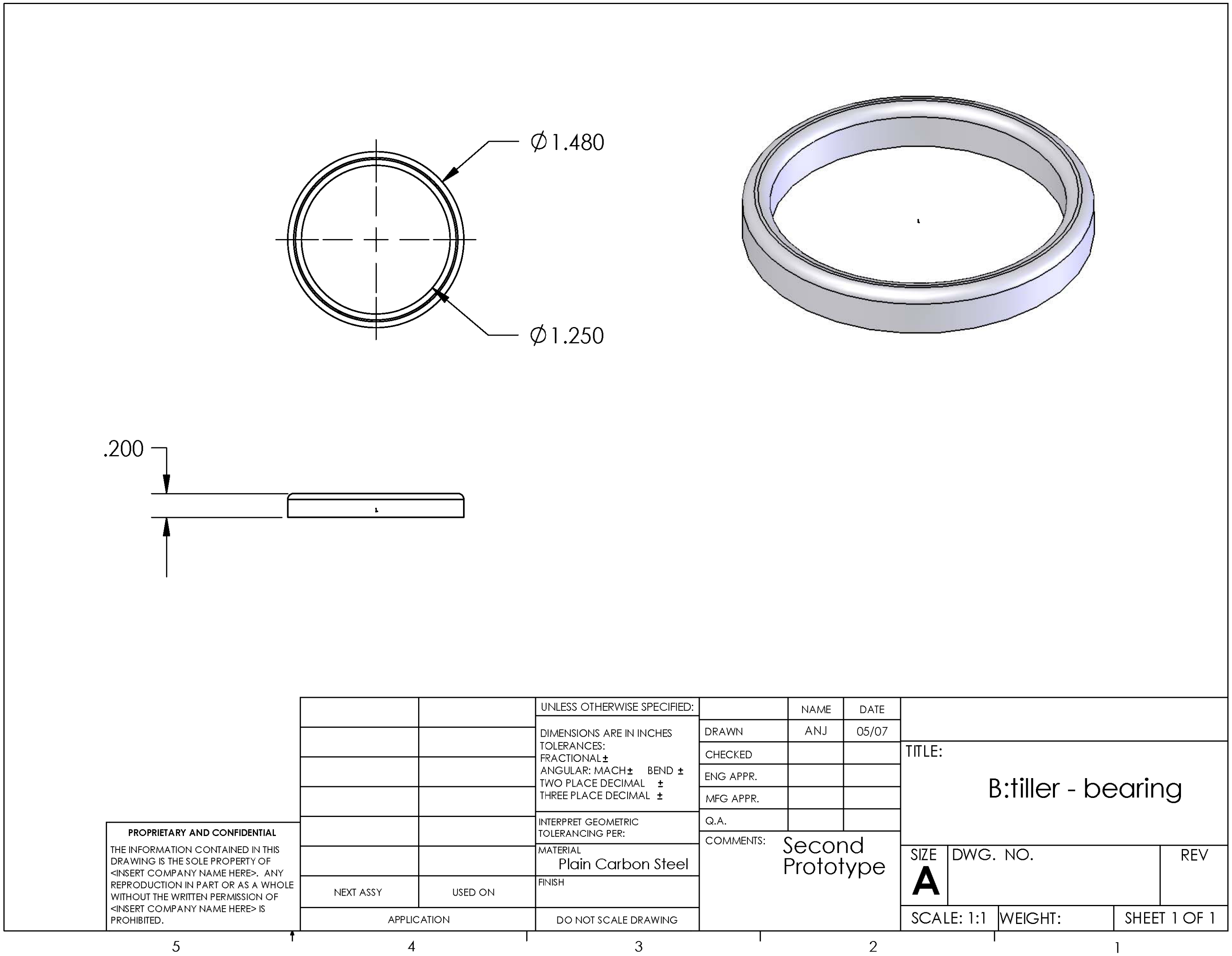
1


∅1.480
∅1.250
.200
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
B:tiller - bearing
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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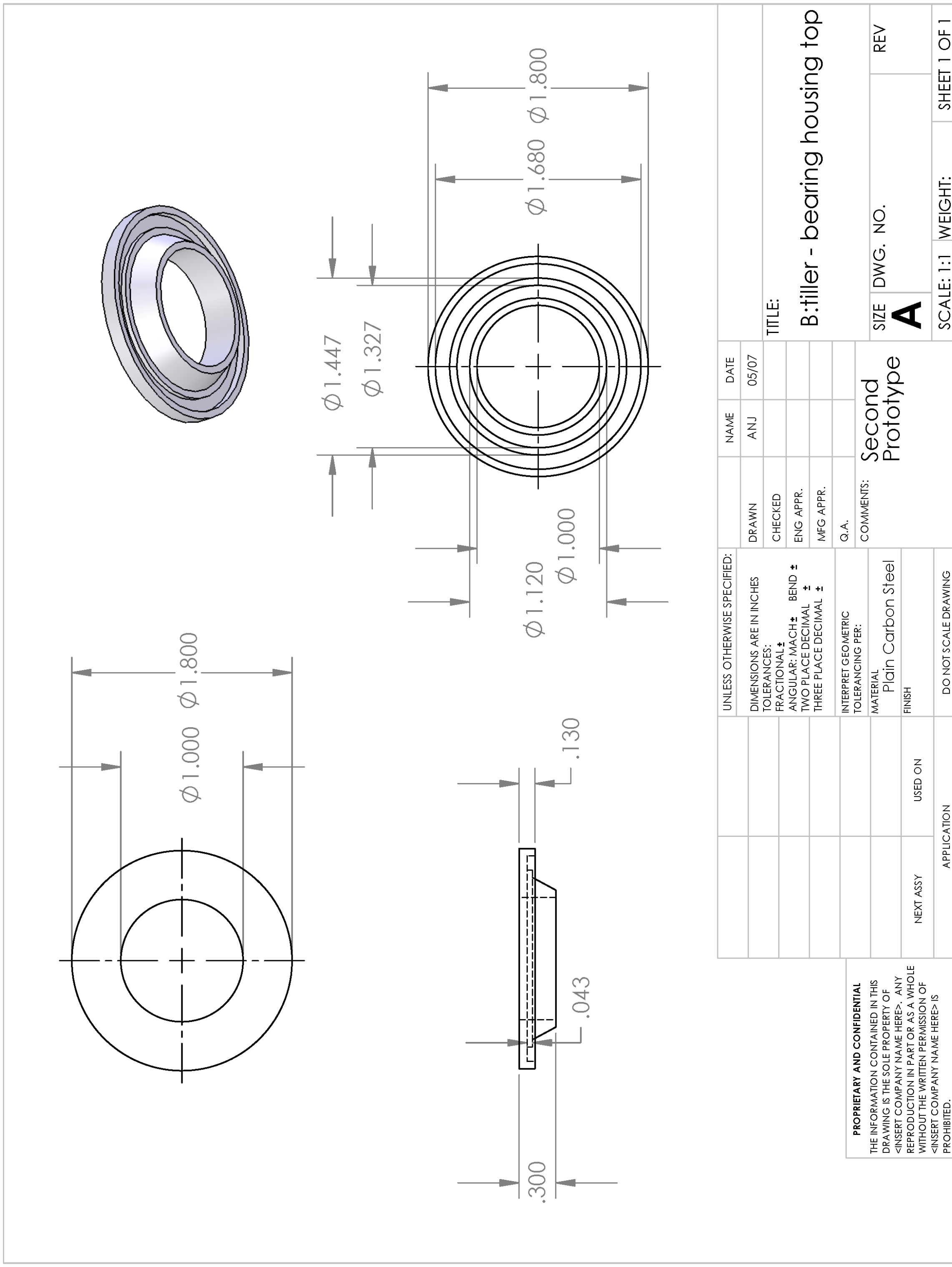

Ø1.000 Ø1.800
.130
.043
.300
Ø1.447
Ø1.327
Ø1.680 Ø1.800
Ø1.120
Ø1.000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
B:tiller - bearing housing top
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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5
4
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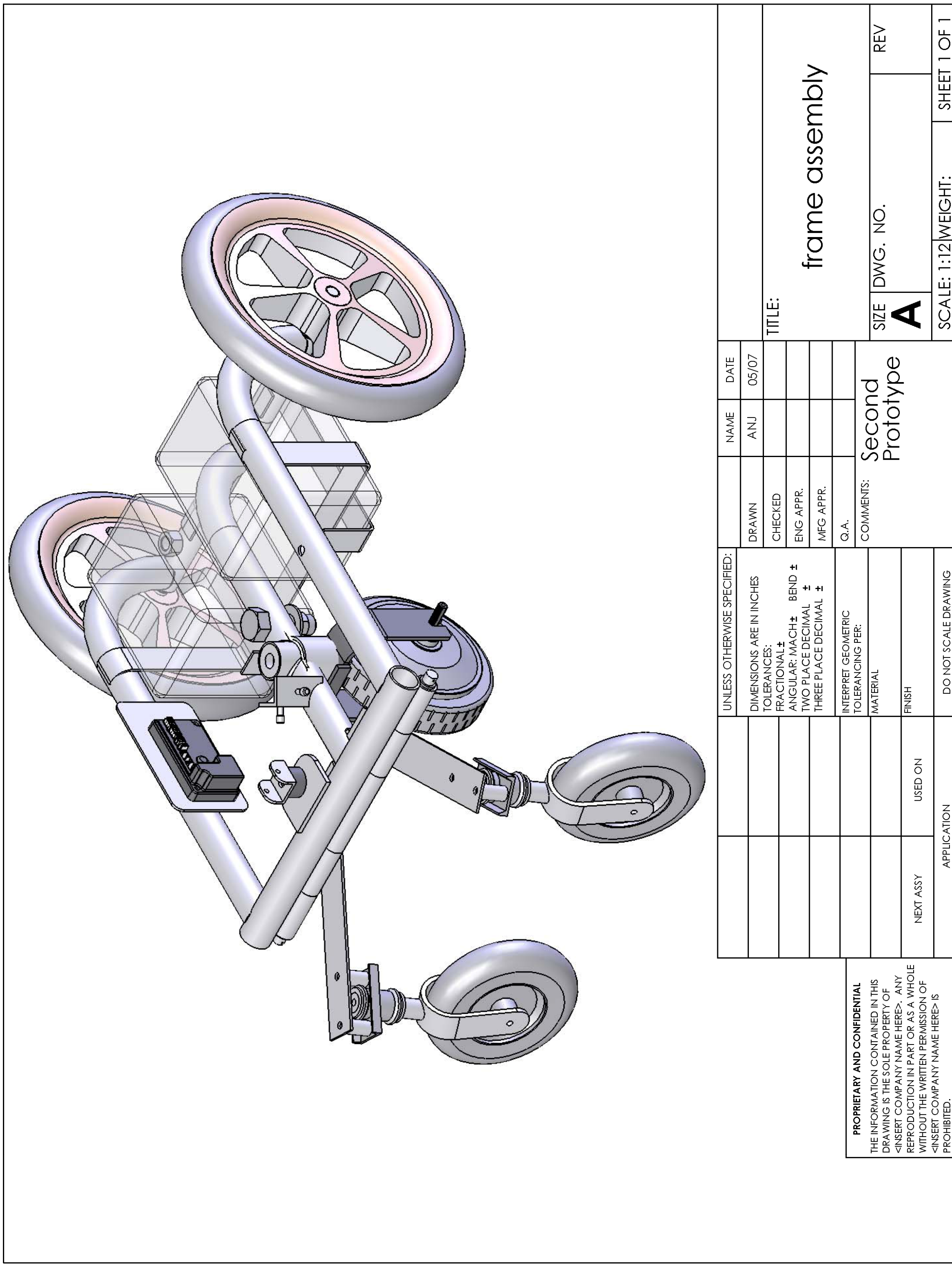
2
1

B.5 FRAME

The main structure of the frame is composed of four pieces of large-diameter tubing. The lateral portions of the frame have a 4” radius bend towards the front of the device, where they connect to a cross-tube which houses the axle and forms the pivot for the swing-arm. The cross-tube on the opposite ends of the lateral tubes support the pivots for the leaf-spring suspension system. Battery support straps, along with a controller-mounting plate are welded onto the frame.


UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
frame assembly
SIZE
A
DWG. NO.
REV
SCALE: 1:12
WEIGHT:
SHEET 1 OF 1
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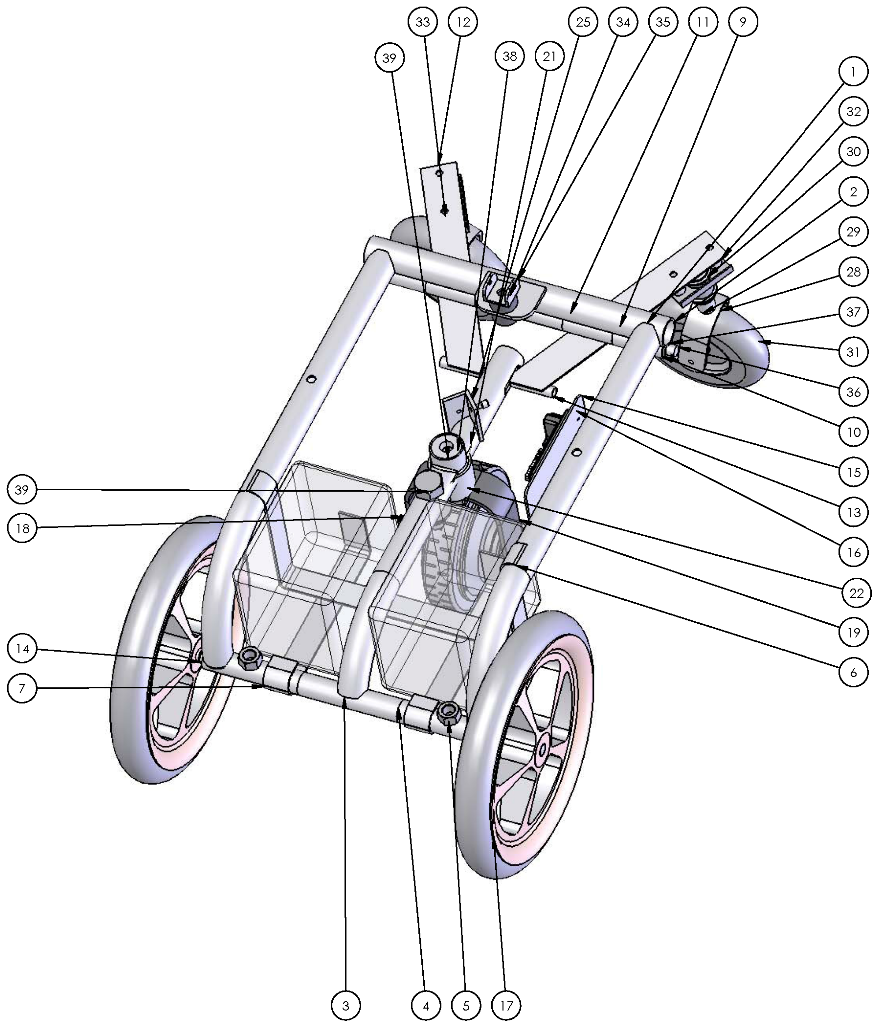
1
2
3
4
5



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	frame - main		2
2	frame - cross back		1
3	frame - swingarm		1
4	frame - cross front outside		1
5	frame - cross front outside		2
6	battery hanger - cross		1
7	battery hanger - front		2
8	battery		2
9	frame - cross back pivot		2
10	frame - cross back fixed		2
11	frame - cross back fixed		1
12	suspension - leaf		2
13	suspension - swingarm link		2
14	axle		1
15	Controler Mounting Plate		1
16	280-1445M		1
17	16inch wheel		2
18	8-wb		1
19	280-1273M-P		1
20	280-1098M		1
21	drive wheel - steering		1
22	drive wheel - bolt stop		2
23	drive wheel - thrust bearing		1
24	suspension - bearing		1
25	frame - cord angle		1
26	frame - cross front bushing		1
27	frame - cross front bushing		2
28	suspension - caster fork fork		2
29	suspension - caster fork axle		2
30	suspension - caster fork bearing		4
31	suspension - caster		2
32	suspension - axle plate		2
33	suspension - spacer		4
34	seat - bumper		2
35	frame - seat adjustment bracket		1
36	frame - cross front bushing insert		1
37	frame - cross back bushing		1
38	Hex Nut_Al		5
39	Hex Bolt_Al		2
40	Flat Washer Type A Narrow_Al		1

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APPLICATION | DO NOT SCALE DRAWING

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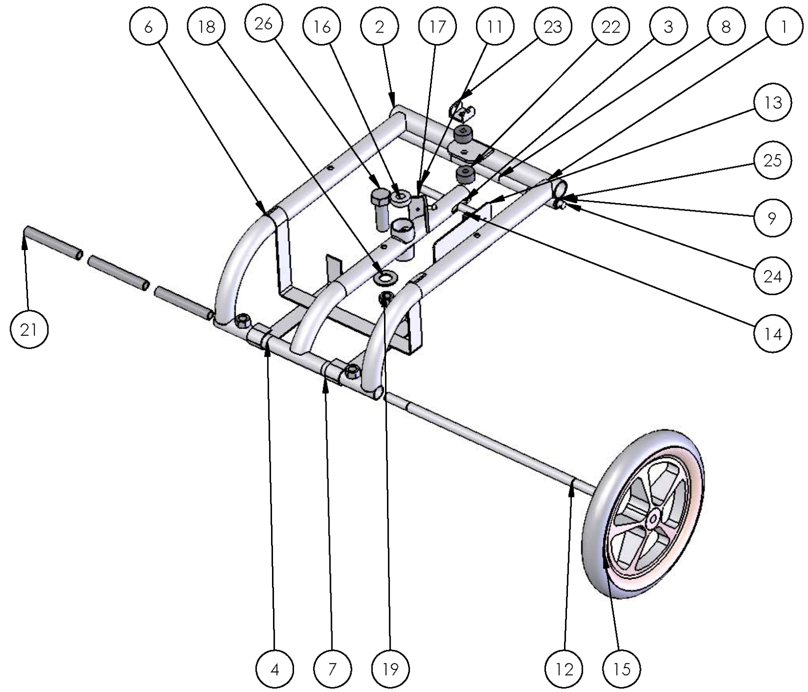
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:
Frame Assembly
SIZE C | DWG. NO. | REV
SCALE: 1:24 | WEIGHT: | SHEET 3 OF 10



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	frame - main		2
2	frame - cross back		1
3	frame - swingarm		1
4	frame - cross front outside		1
5	frame - cross front outside		2
6	battery hanger - cross		1
7	battery hanger - front		2
8	frame - cross back pivot		2
9	frame - cross back fixed		2
10	frame - cross back fixed		1
11	suspension - swingarm link		2
12	axle		1
13	Controler Mounting Plate		1
14	280-1445M		1
15	16inch wheel		1
16	suspension - bearing		1
17	frame - cord angle		1
18	Flat Washer Type A Narrow_AI		1
19	Hex Nut_AI		3
20	frame - cross front bushing		1
21	frame - cross front bushing		2
22	seat - bumper		2
23	frame - seat adjustment bracket		1
24	frame - cross front bushing insert		1
25	frame - cross back bushing		1
26	Hex Bolt_AI		1

NEXT ASSY | USED ON | APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

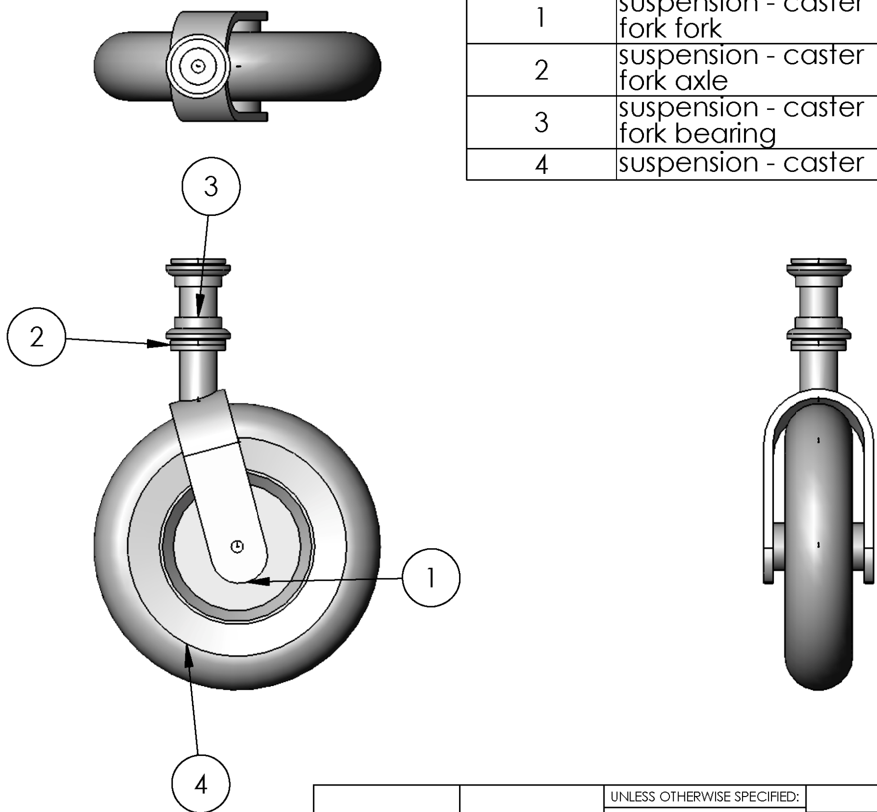
COMMENTS:

TITLE:
Frame Assembly (Detail)

SIZE B | DWG. NO. | REV

SCALE: 1:12 | WEIGHT: | SHEET 8 OF 10

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	suspension - caster fork fork		1
2	suspension - caster fork axle		1
3	suspension - caster fork bearing		2
4	suspension - caster		1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	ANJ	05/07
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS: Second Prototype		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

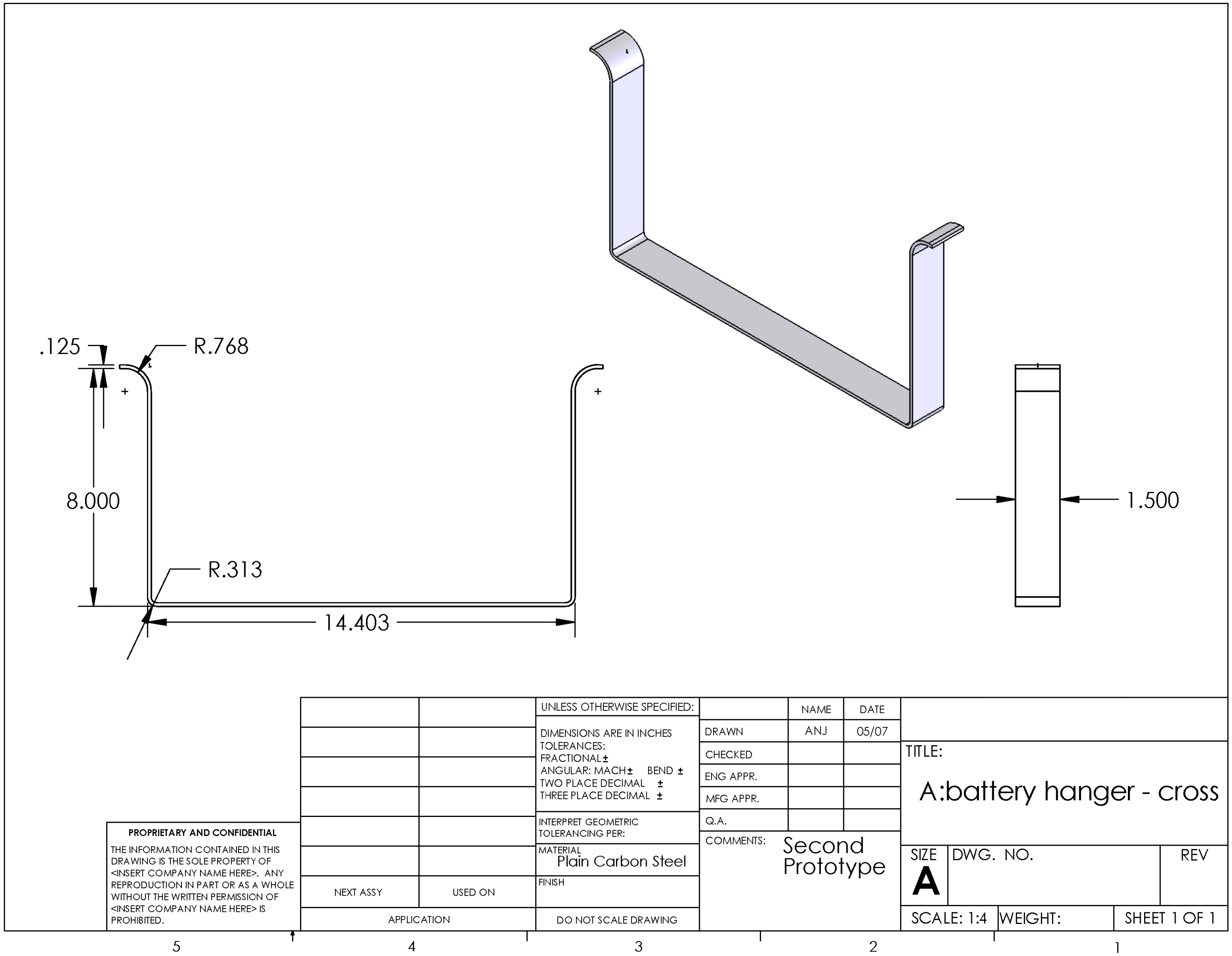
TITLE:

caster fork assembly

SIZE A | DWG. NO. | REV

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1


.125
R.768
8.000
R.313
14.403
1.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:battery hanger - cross
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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NEXT ASSY
USED ON
APPLICATION
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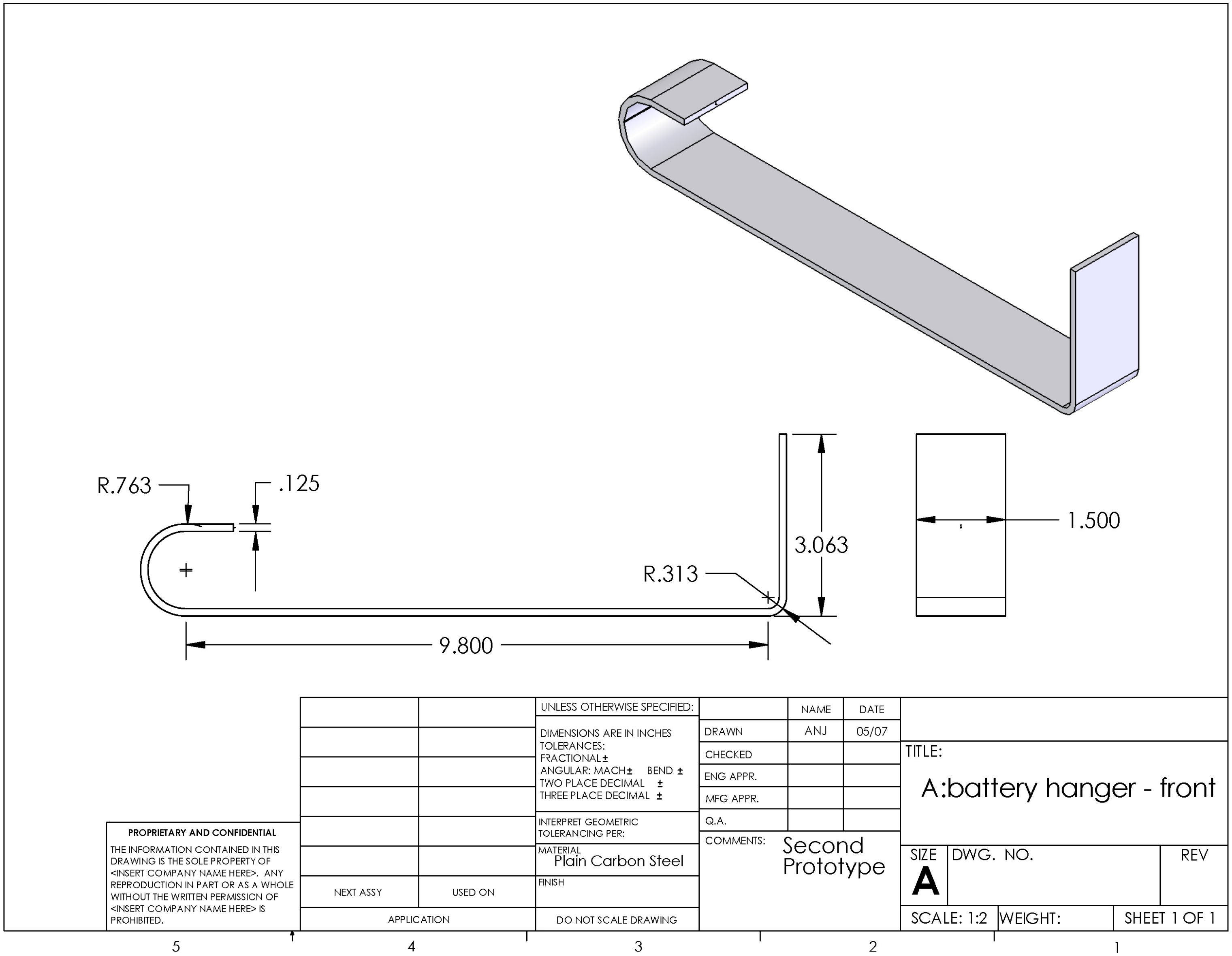
R.763
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R.313
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1.500
PROPRIETARY AND CONFIDENTIAL
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APPLICATION
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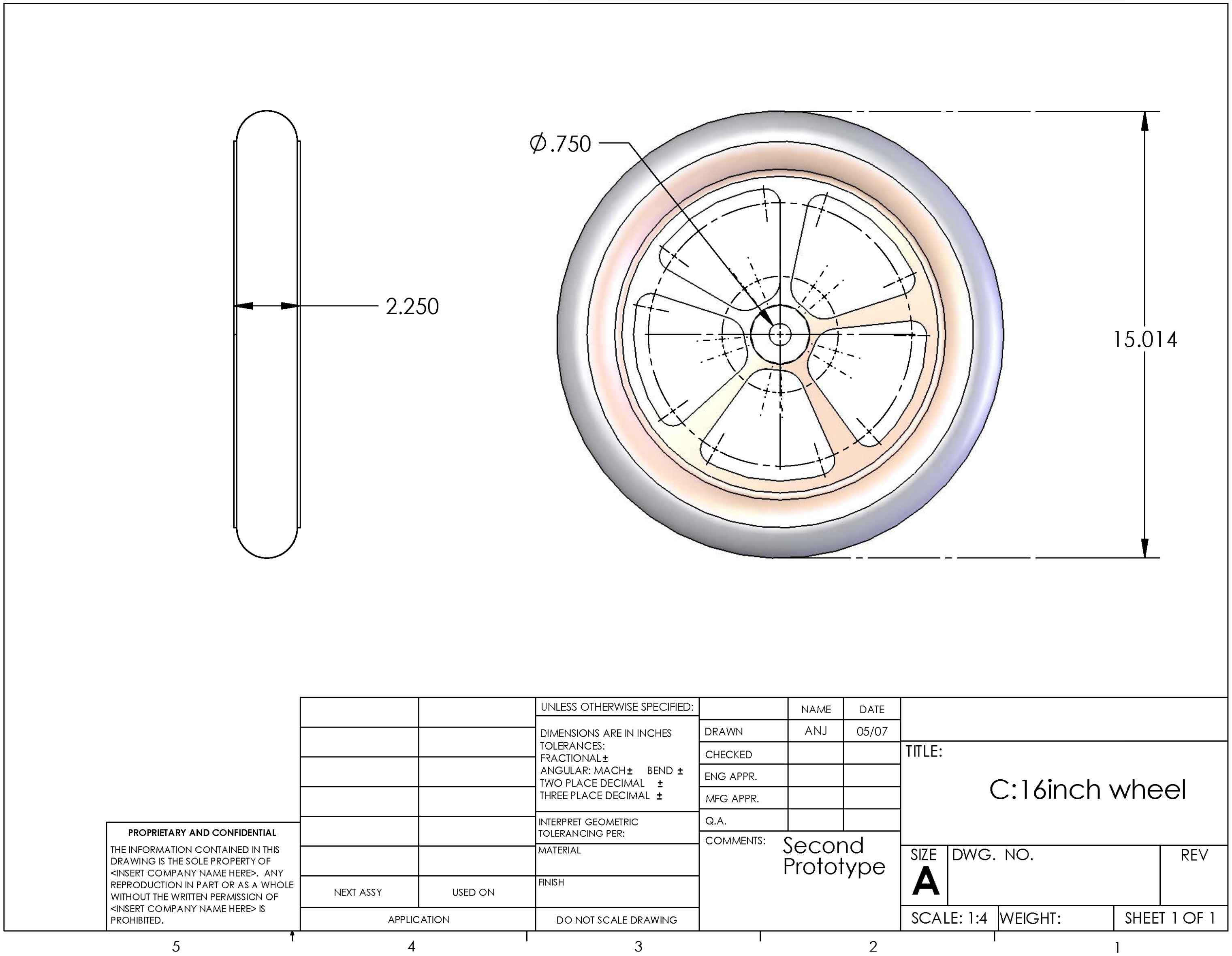
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:battery hanger - front
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



Ø.750
2.250
15.014
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME DATE
DRAWN ANJ 05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
C:16inch wheel
SIZE A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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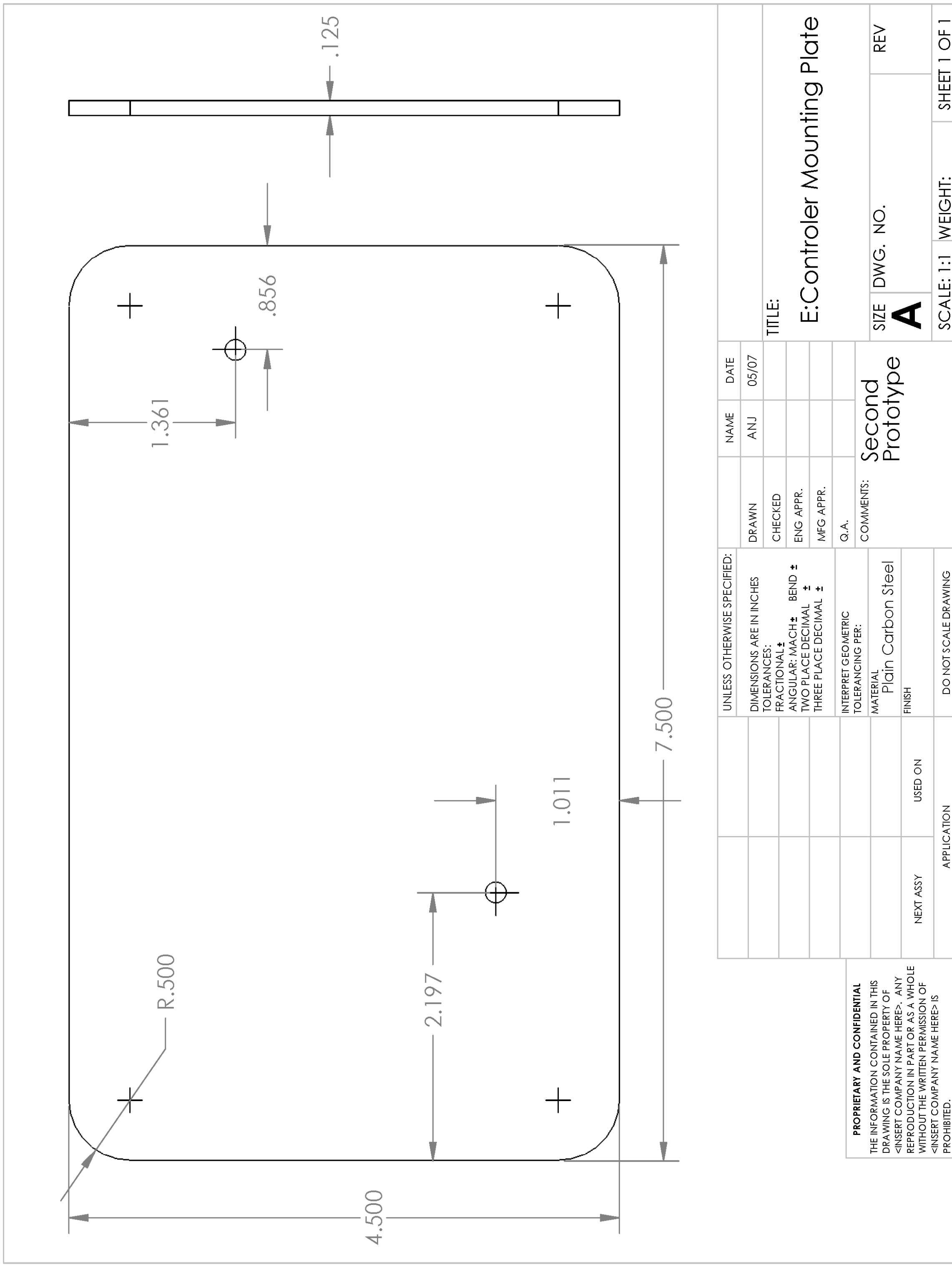
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1.361
7.500
1.011
R.500
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4.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
E:Controler Mounting Plate
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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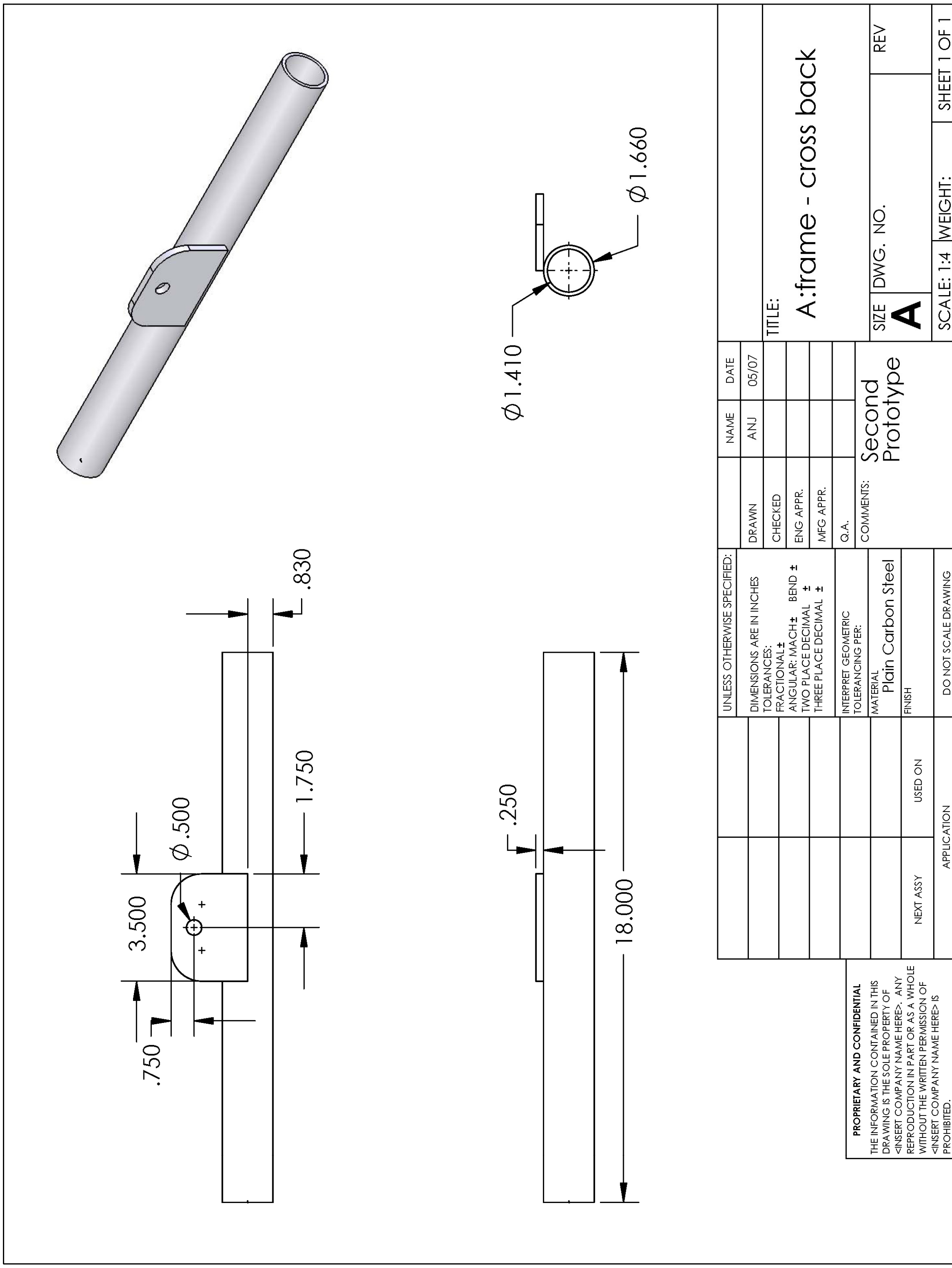
5
4
3
2
1



.750
3.500
Ø.500
1.750
.830
.250
18.000
Ø1.410
Ø1.660
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:frame - cross back
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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5
4
3
2
1


Ø.850
Ø.620
17.500
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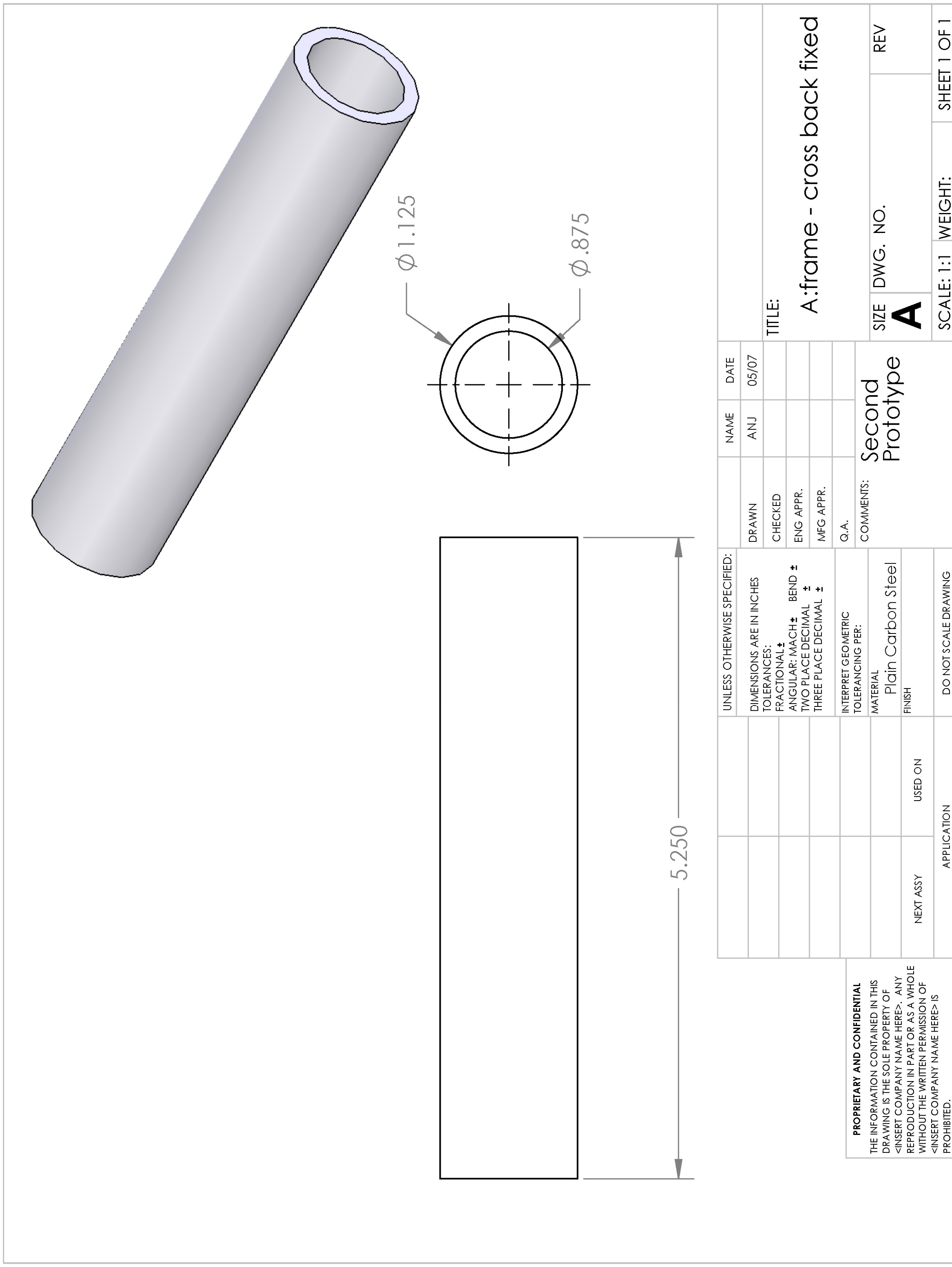
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PVC Rigid
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:frame - cross back bushing
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



Ø1.125
Ø.875
5.250
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
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DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
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2
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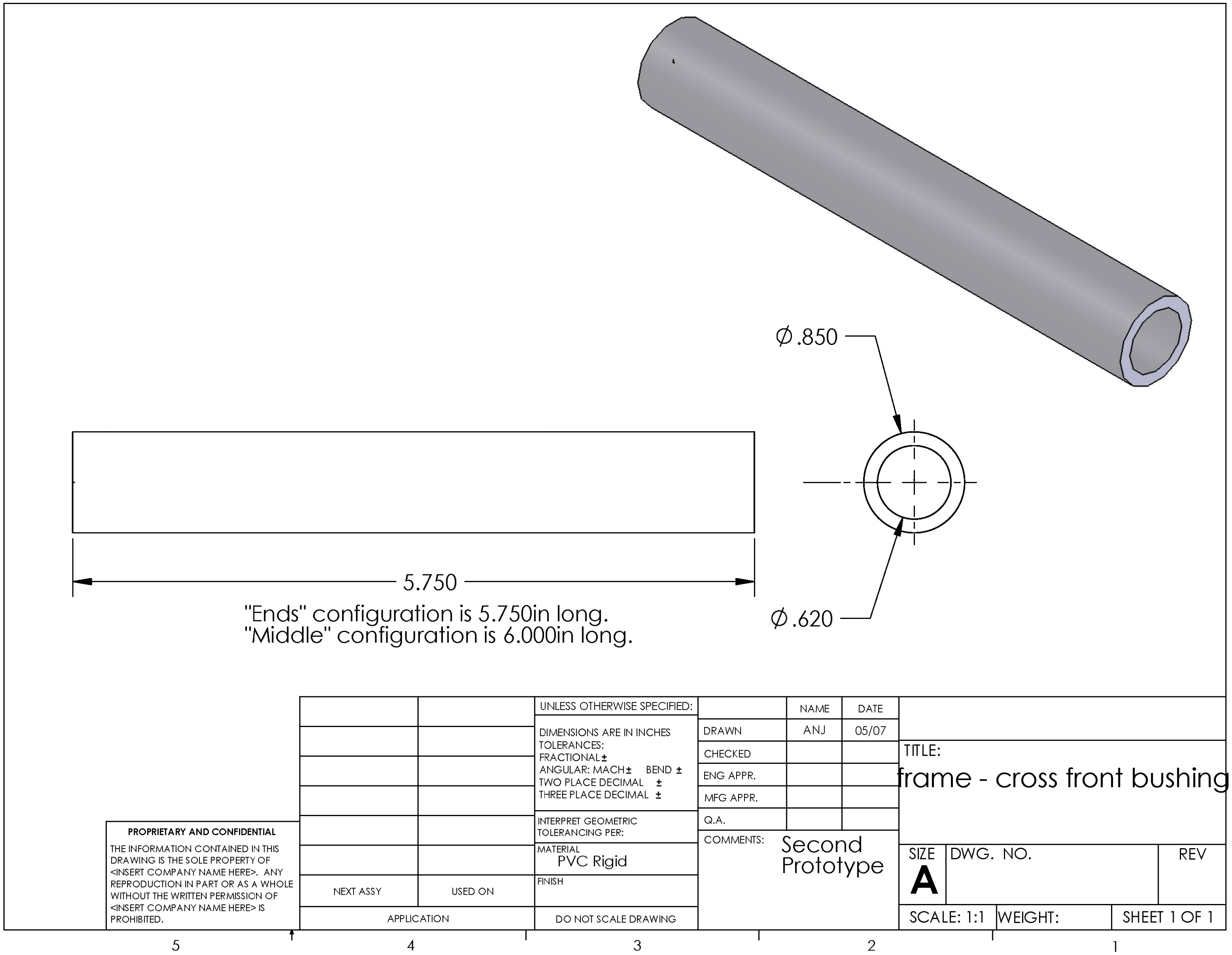
Ø.850
Ø.620
5.750
"Ends" configuration is 5.750in long.
"Middle" configuration is 6.000in long.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PVC Rigid
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
frame - cross front bushing
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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5
4
3
2
1

Ø.620
.310
Ø.100
.150
18.500
Ø.100
.310
.150
PROPRIETARY AND CONFIDENTIAL
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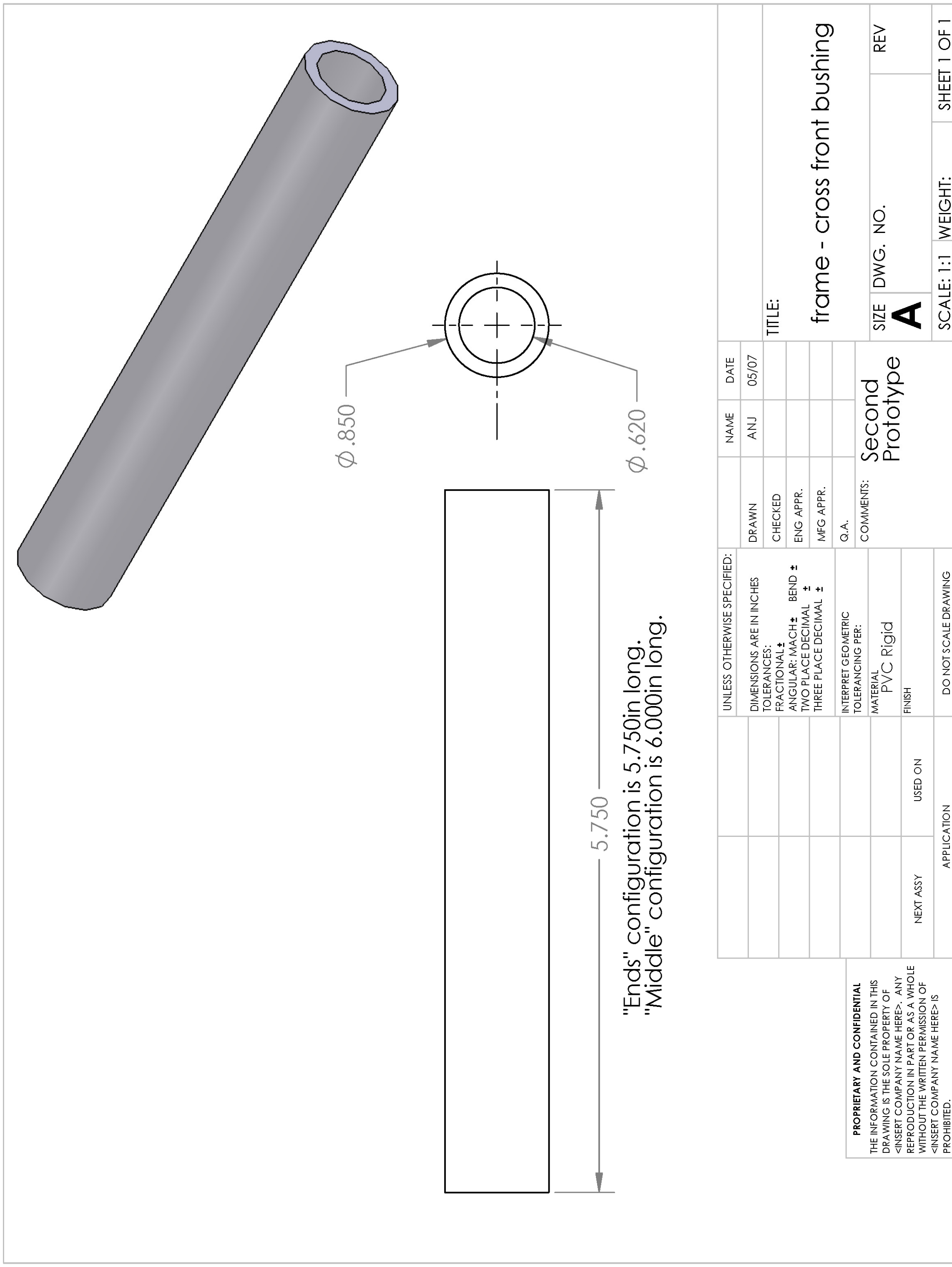
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:frame - cross front bushing insert
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



Ø.850
Ø.620
5.750
"Ends" configuration is 5.750in long.
"Middle" configuration is 6.000in long.
PROPRIETARY AND CONFIDENTIAL
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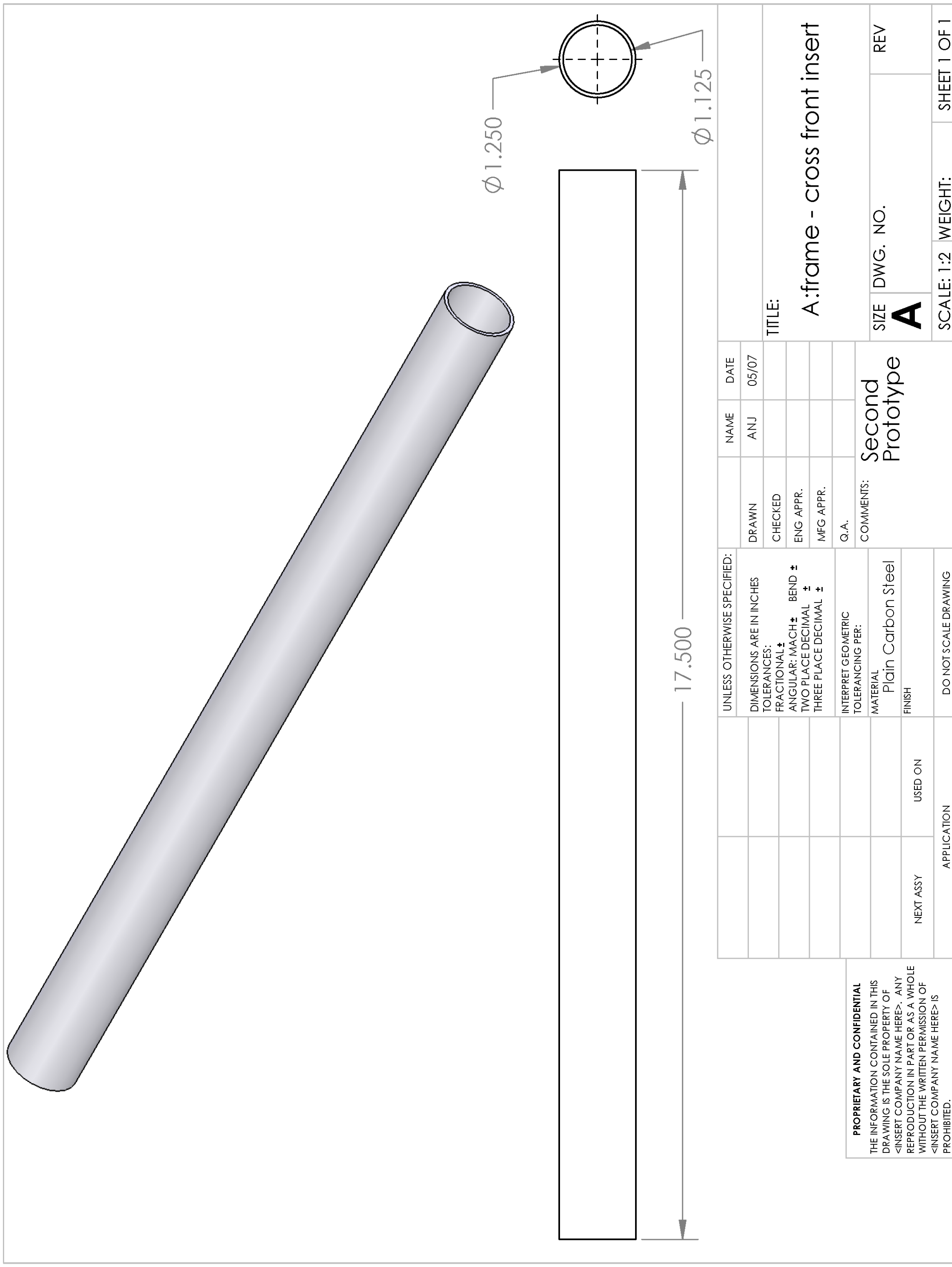
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PVC Rigid
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
frame - cross front bushing
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



Ø1.250
Ø1.125
17.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:frame - cross front insert
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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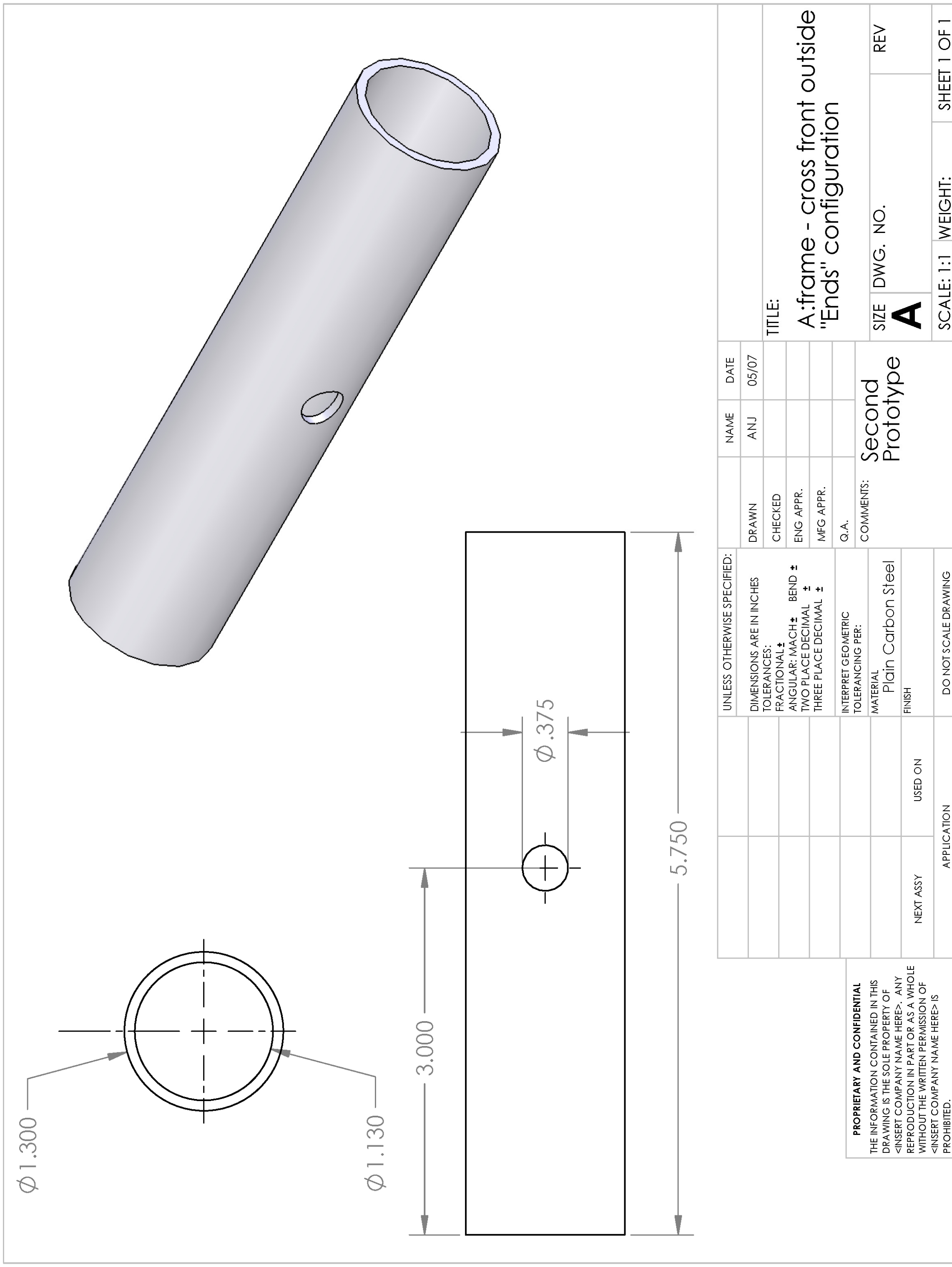
5
4
3
2
1


Ø1.300
Ø1.130
3.000
Ø.375
5.750
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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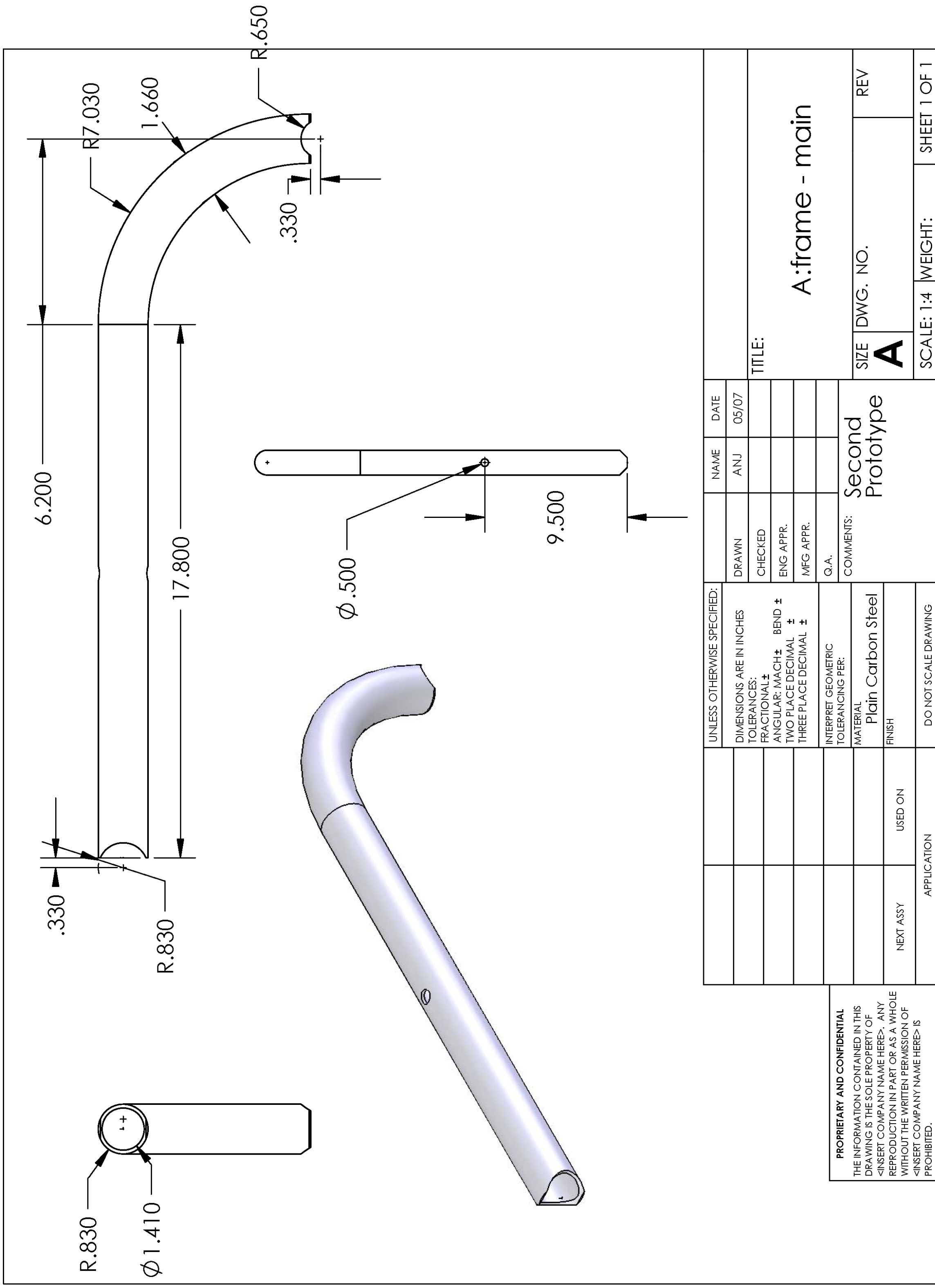
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:frame - cross front outside "Ends" configuration
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
1
2
3
4
5



R.650
R7.030
1.660
6.200
.330
17.800
.330
R.830
Ø.500
9.500
R.830
Ø1.410
PROPRIETARY AND CONFIDENTIAL
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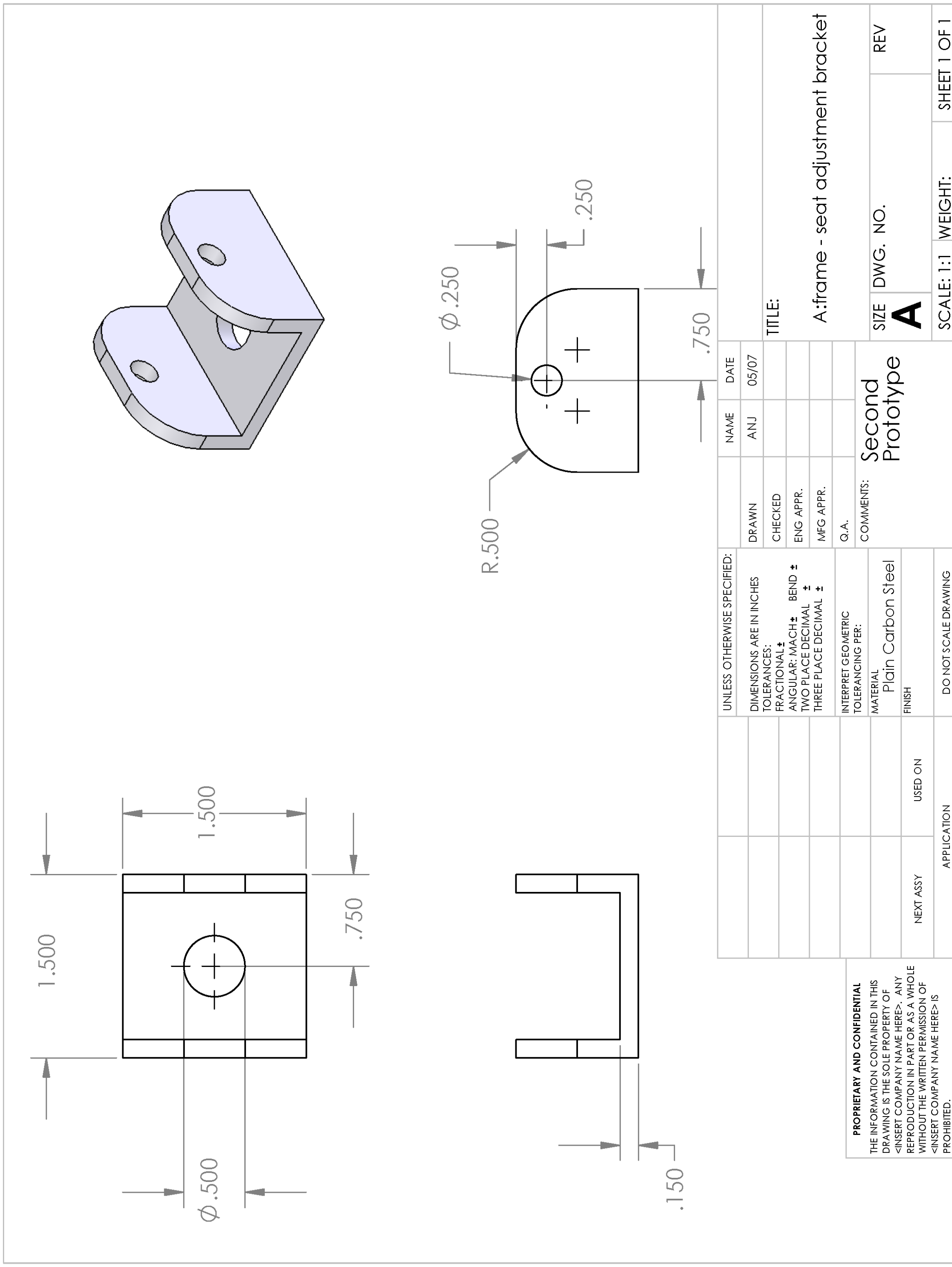
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:frame - main
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1


1.500
1.500
.750
Ø.500
.150
Ø.250
.250
.750
R.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:frame - seat adjustment bracket
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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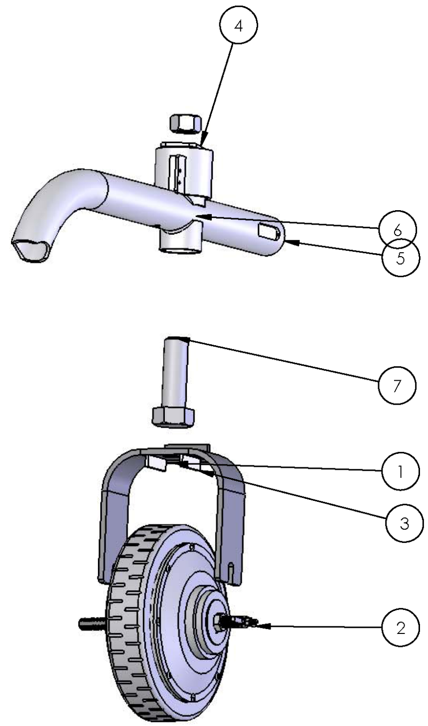
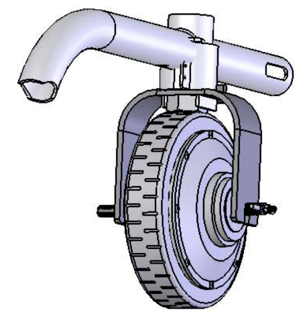
5
4
3
2
1

B.6 SWING ARM

One end of the swing-arm pivots about the axle of the large 16” wheels of the HyPoV. The second end connects to the leaf-springs of the suspension system through a slotted hole. A bearing housing system is welded the swing-arm near mid-span, to support the Timken roller bearing (bottom) and sealed ball bearing (top). This bearing system accepts the hub-motor fork stem, and allows the device to be steered. A ½” bolt that passes through the swing-arm near the bearing system is used as a steering limiter. A piece of angle-iron with a birds-mouth notch is welded to the top of the swing-arm to support the cable-ends for the steering system.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	280-1273M-P		1
2	8-wb		1
3	drive wheel - bolt stop		2
4	drive wheel - steering		1
5	frame - swingarm		1
6	Hex Nut_Al		2
7	Hex Bolt_Al		1





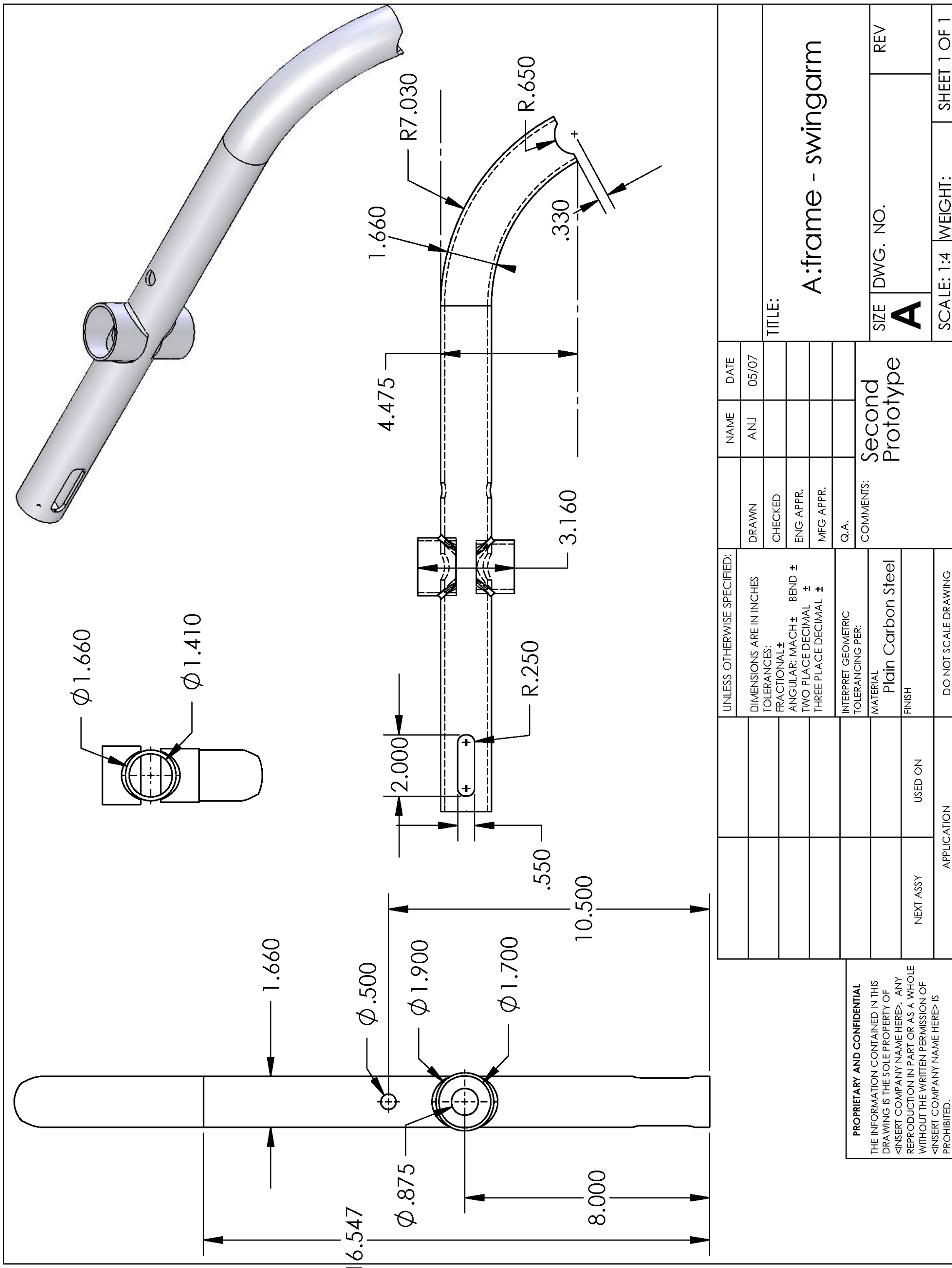
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Drive Wheel Assembly

SIZE	DWG. NO.	REV
B		

SCALE: 1:8 | WEIGHT: | SHEET 6 OF 10


Ø1.660
Ø1.410
R.250
2.000
.550
3.160
4.475
1.660
R7.030
R.650
.330
1.660
Ø.500
Ø1.900
Ø1.700
10.500
Ø.875
8.000
16.547
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:frame - swingarm
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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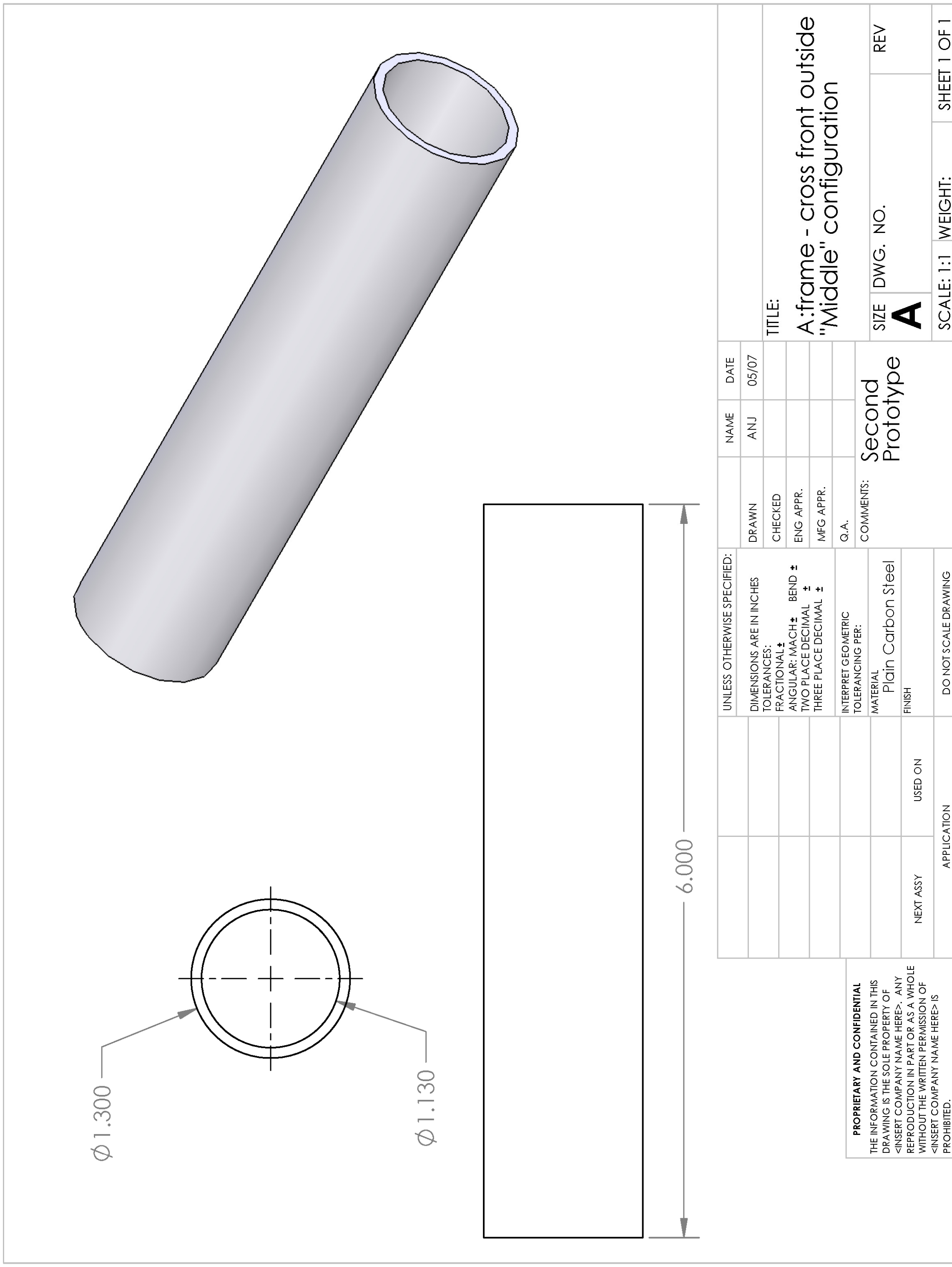
5
4
3
2
1


Ø1.300
Ø1.130
6.000
PROPRIETARY AND CONFIDENTIAL
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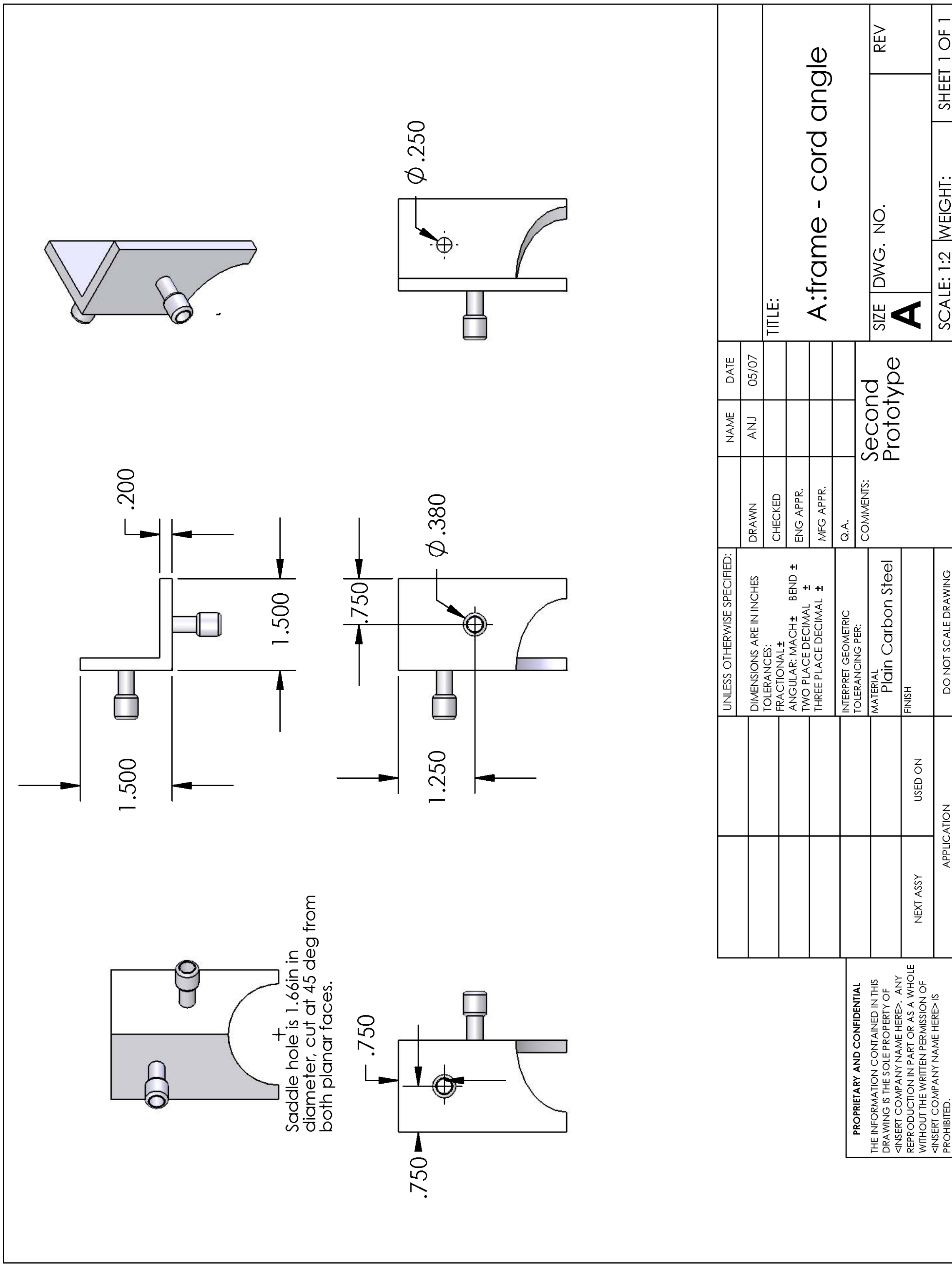
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:frame - cross front outside "Middle" configuration
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


.200
1.500
1.500
.750
1.250
Ø.380
Ø.250
.750
.750
Saddle hole is 1.66in in diameter, cut at 45 deg from both planar faces.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:frame - cord angle
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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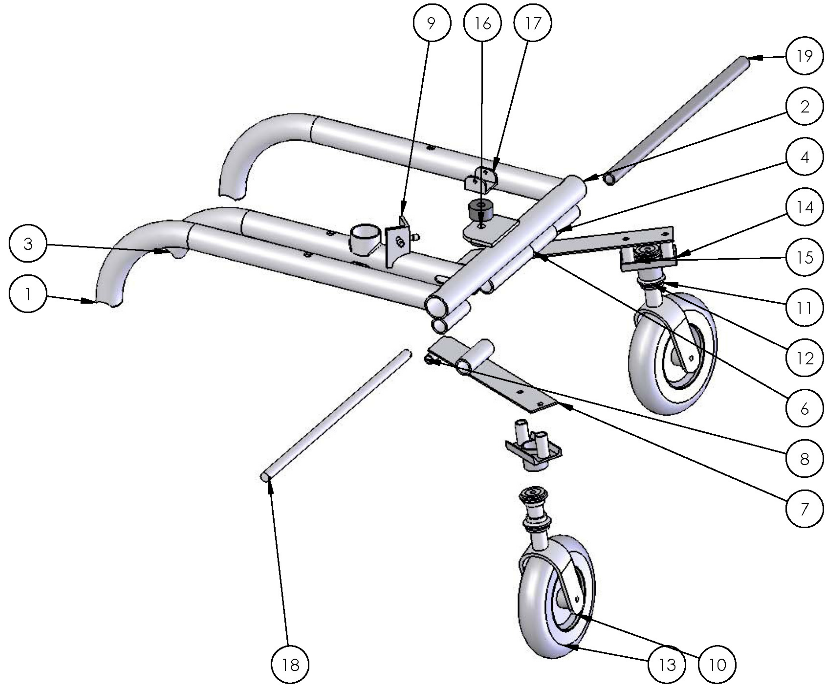
B.7 SUSPENSION

The leaf-spring suspension system was fabricated from 1095 steel plate, and was heat-treated to achieve spring-steel behavior. Two pieces of round-tubing are welded at a 30 deg angle to the centerline (on at the end, and one at mid-span) of the leaf-spring to form a pivot point at the frame and a pivot point where the spring connects to the swing-arm, respectively. A caster is attached to the trailing end of the leaf-spring and is mounted rigid to the end of the leaf spring.

The suspension system includes both the action of the casters (which can move independently of each other) and the motion of the swing arm. The load balance that is achieved through the leaf spring (which distributes load from the frame to the caster and swing-arm) works to keep both the casters and the hub-motor in contact with the ground at all times, regardless of the terrain the HyPoV is traversing.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	frame - main		2
2	frame - cross back		1
3	frame - swingarm		1
4	frame - cross back pivot		2
5	frame - cross back fixed		2
6	frame - cross back fixed		1
7	suspension - leaf		2
8	suspension - swingarm link		2
9	frame - cord angle		1
10	suspension - caster fork fork		2
11	suspension - caster fork axle		2
12	suspension - caster fork bearing		4
13	suspension - caster		2
14	suspension - axle plate		2
15	suspension - spacer		4
16	seat - bumper		2
17	frame - seat adjustment bracket		1
18	frame - cross front bushing insert		1
19	frame - cross back bushing		1



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NEXT ASSY | USED ON | APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

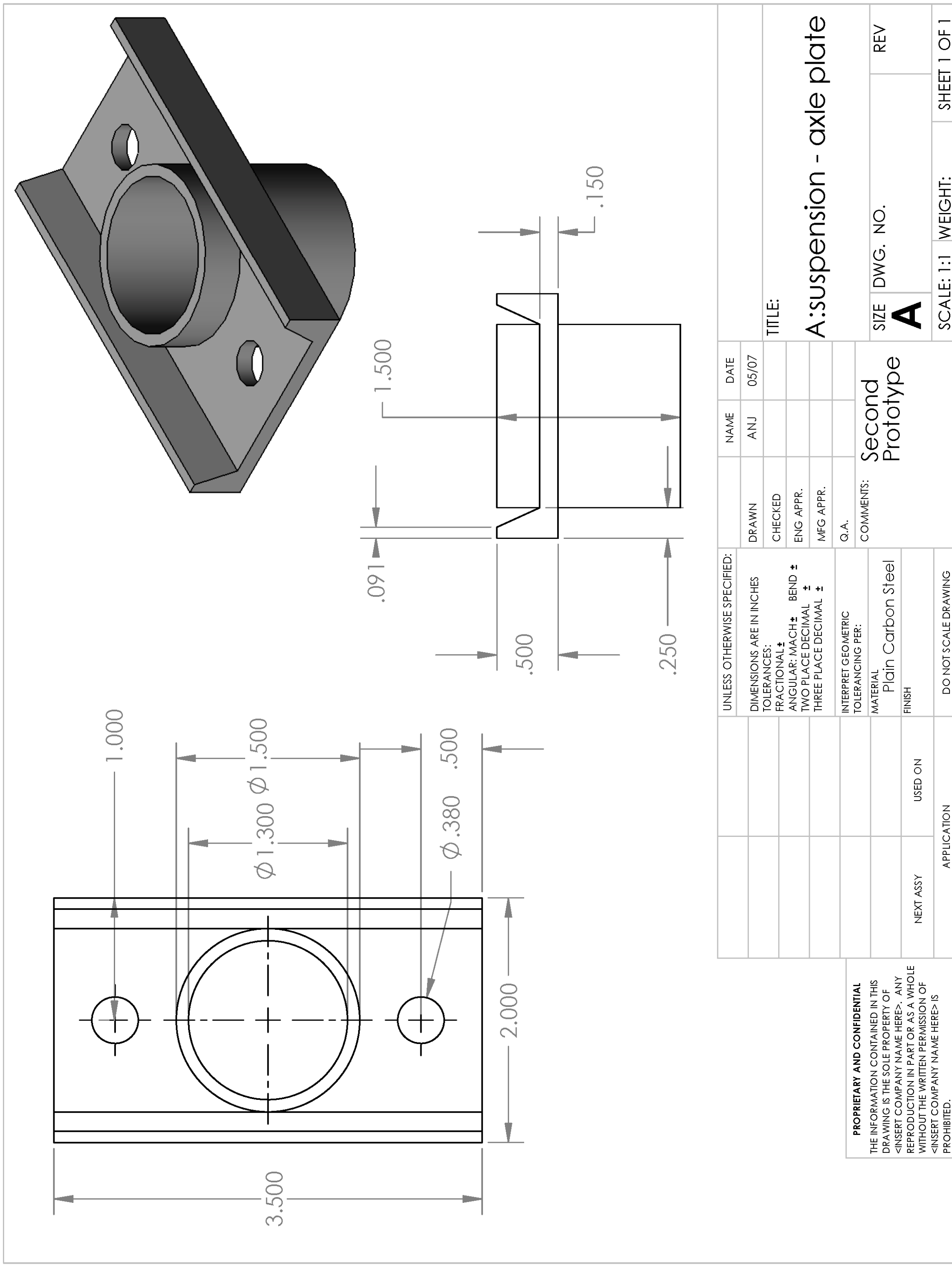
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

DRAWN | CHECKED | ENG APPR. | MFG APPR. | Q.A. | COMMENTS: | NAME | DATE

TITLE: Suspension Assembly

SIZE B | DWG. NO. | REV

SCALE: 1:12 | WEIGHT: | SHEET 7 OF 10



A:suspension - axle plate
TITLE:
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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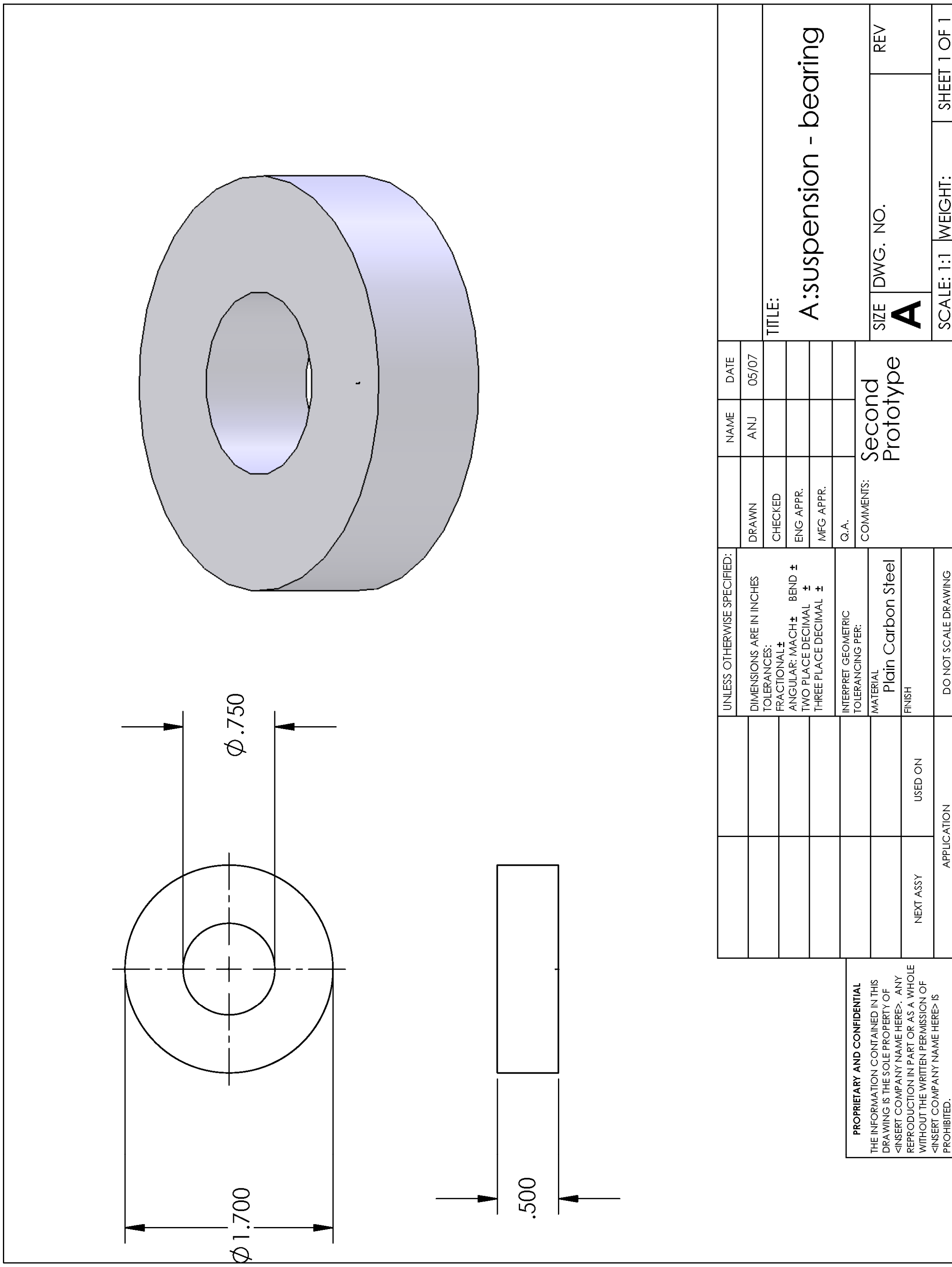
3.500
2.000
1.000
Ø1.300
Ø1.500
.500
Ø.380
.091
.500
.250
1.500
.150
1
2
3
4
5



Ø 1.700
Ø .750
.500
A:suspension - bearing
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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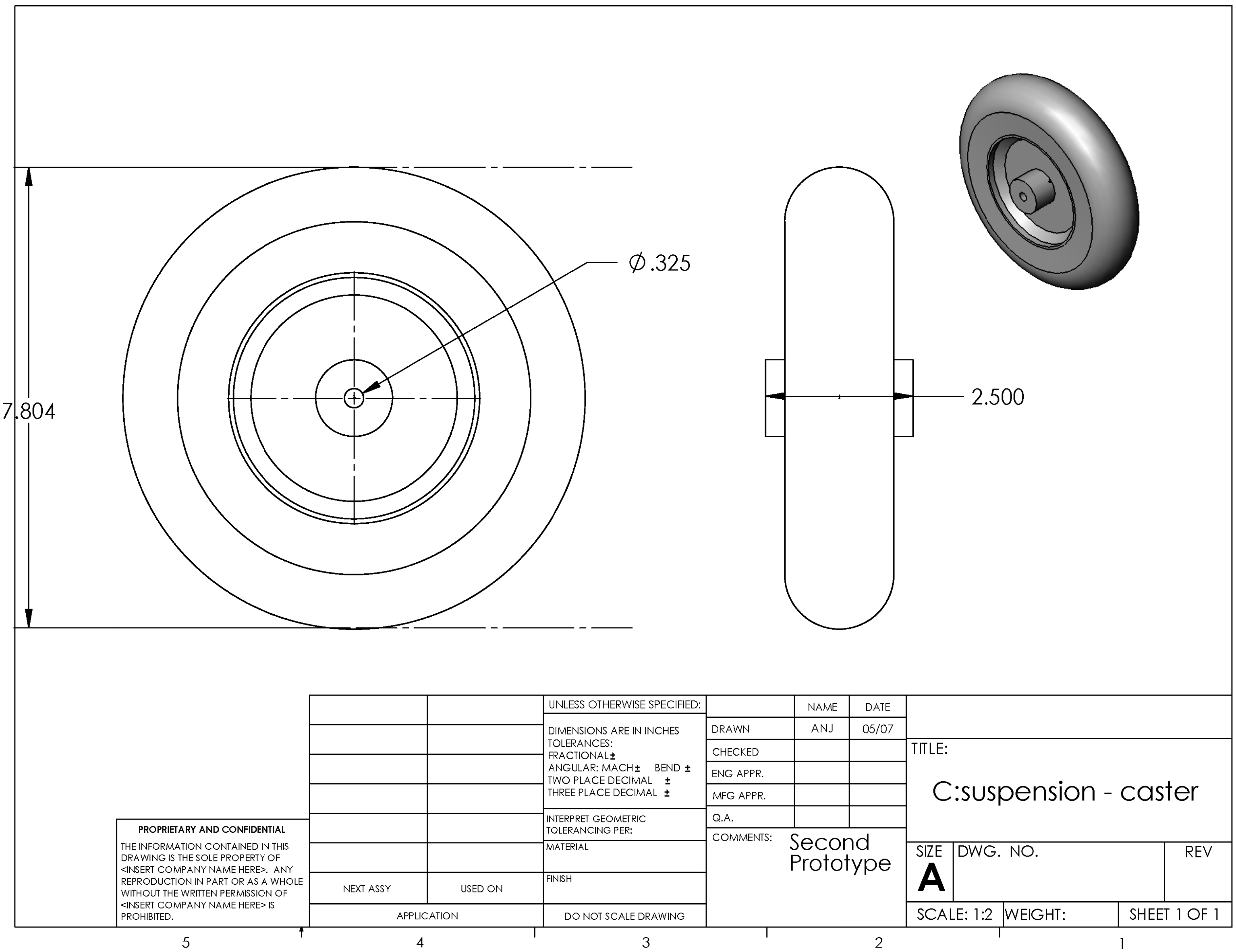
1
2
3
4
5


7.804
Ø.325
2.500
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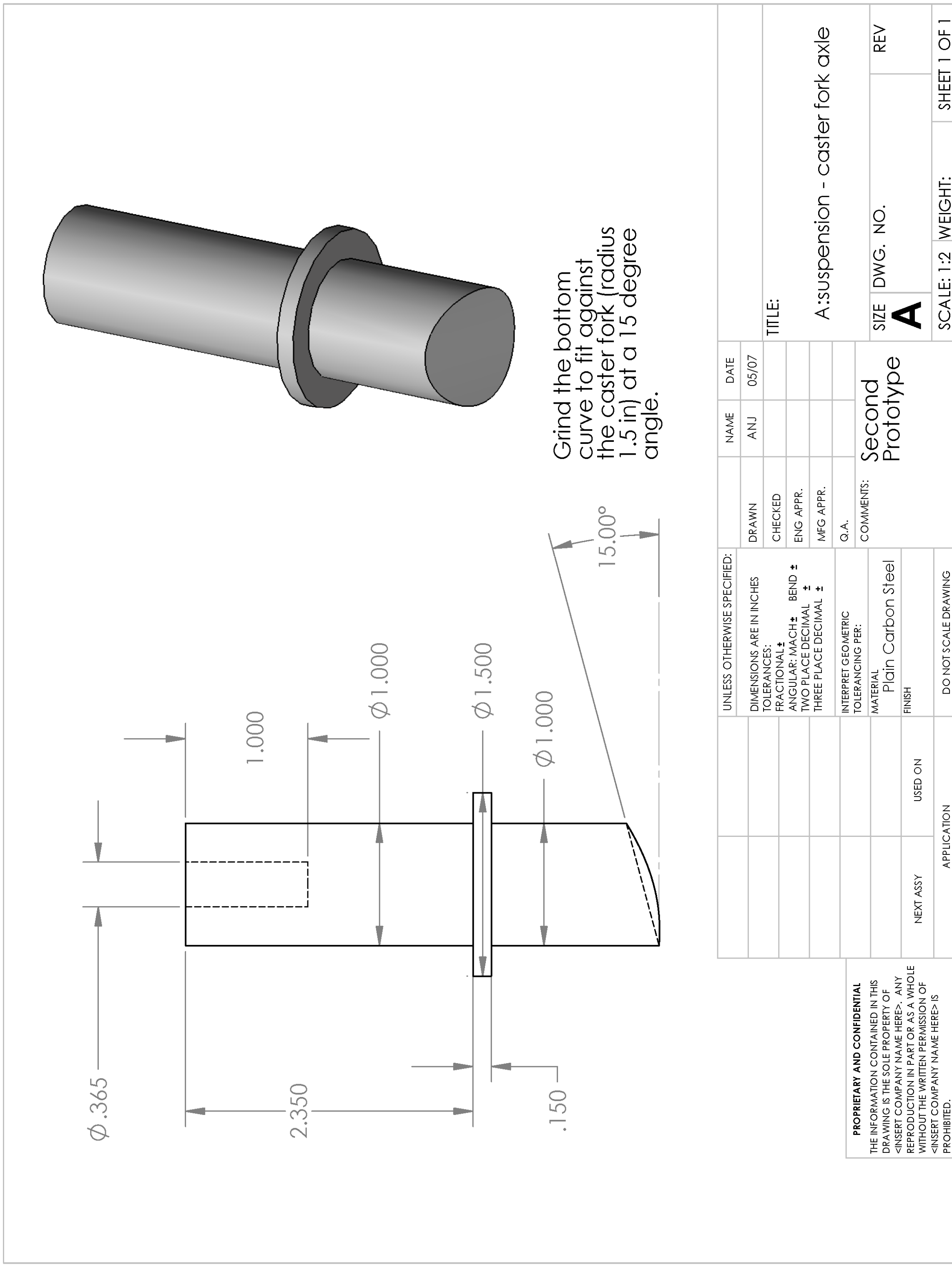
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
C:suspension - caster
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


Ø.365
2.350
.150
1.000
Ø1.000
Ø1.500
Ø1.000
15.00°
Grind the bottom curve to fit against the caster fork (radius 1.5 in) at a 15 degree angle.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:suspension - caster fork axle
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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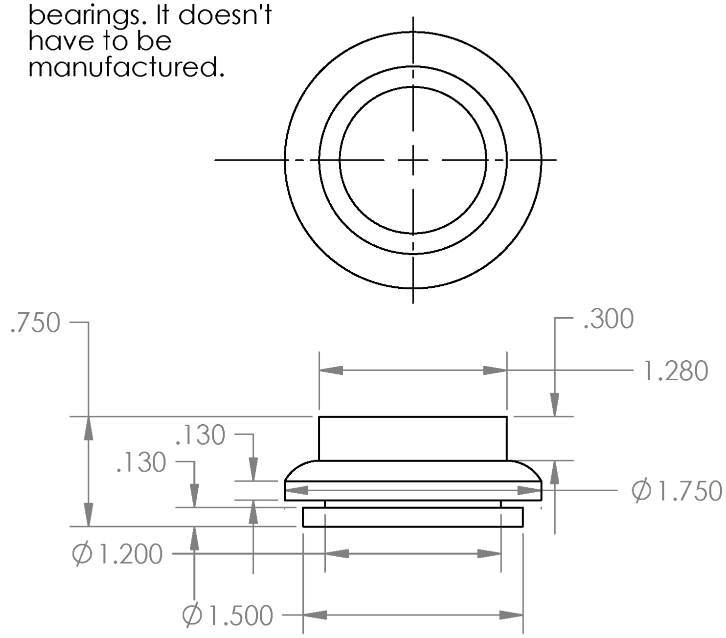
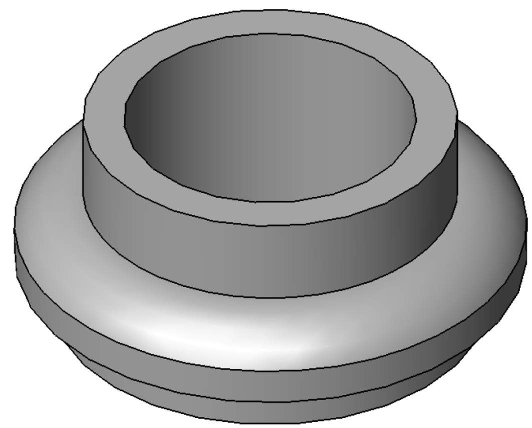
This part is hardware and consists of various bearings. It doesn't have to be manufactured.





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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Plain Carbon Steel

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	ANJ	05/07
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS: Second Prototype

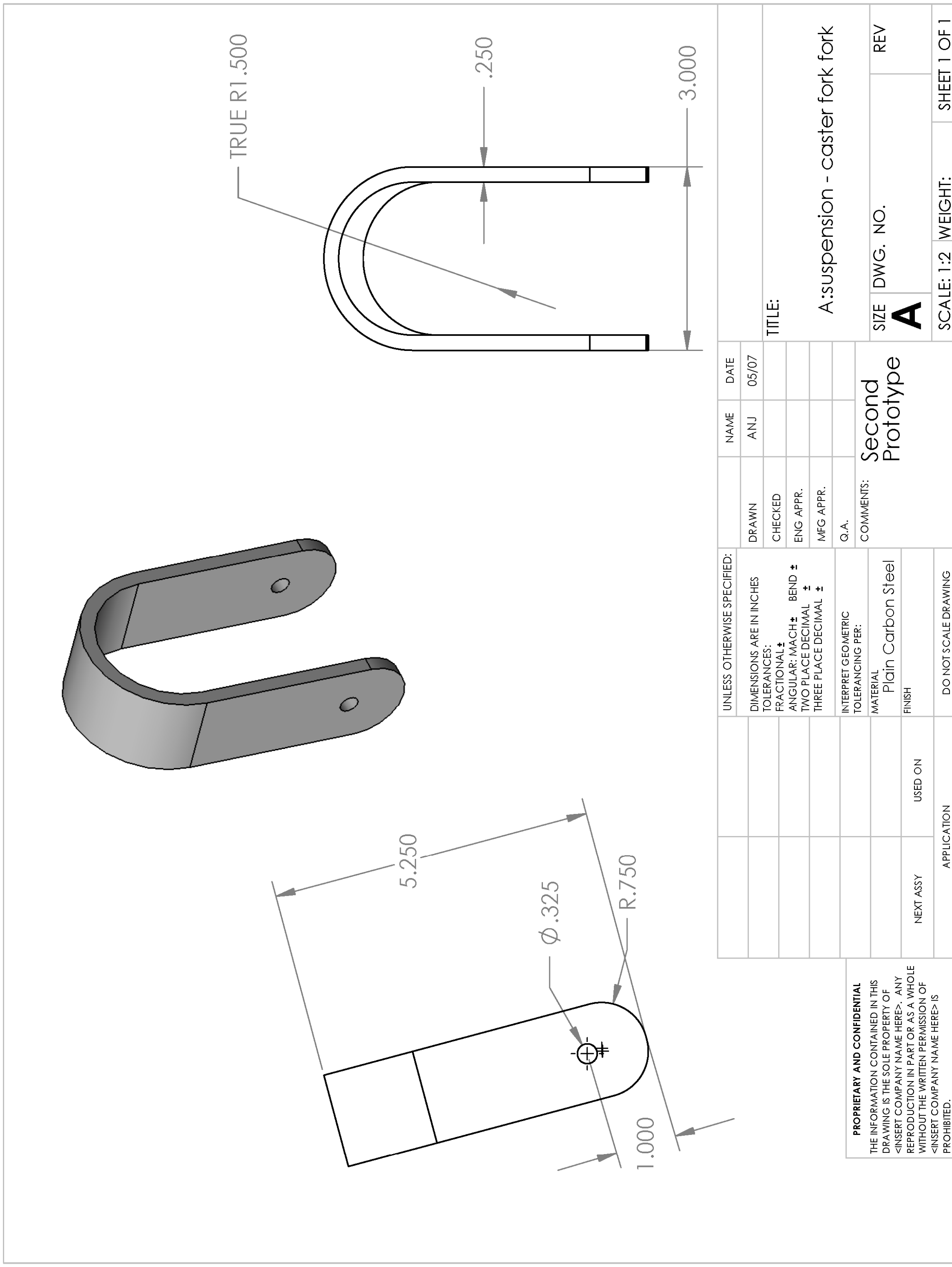
TITLE:

A:suspension - caster fork bearing

SIZE A | DWG. NO. | REV

SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



TRUE R1.500
.250
3.000
5.250
Ø.325
R.750
1.000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:suspension - caster fork fork
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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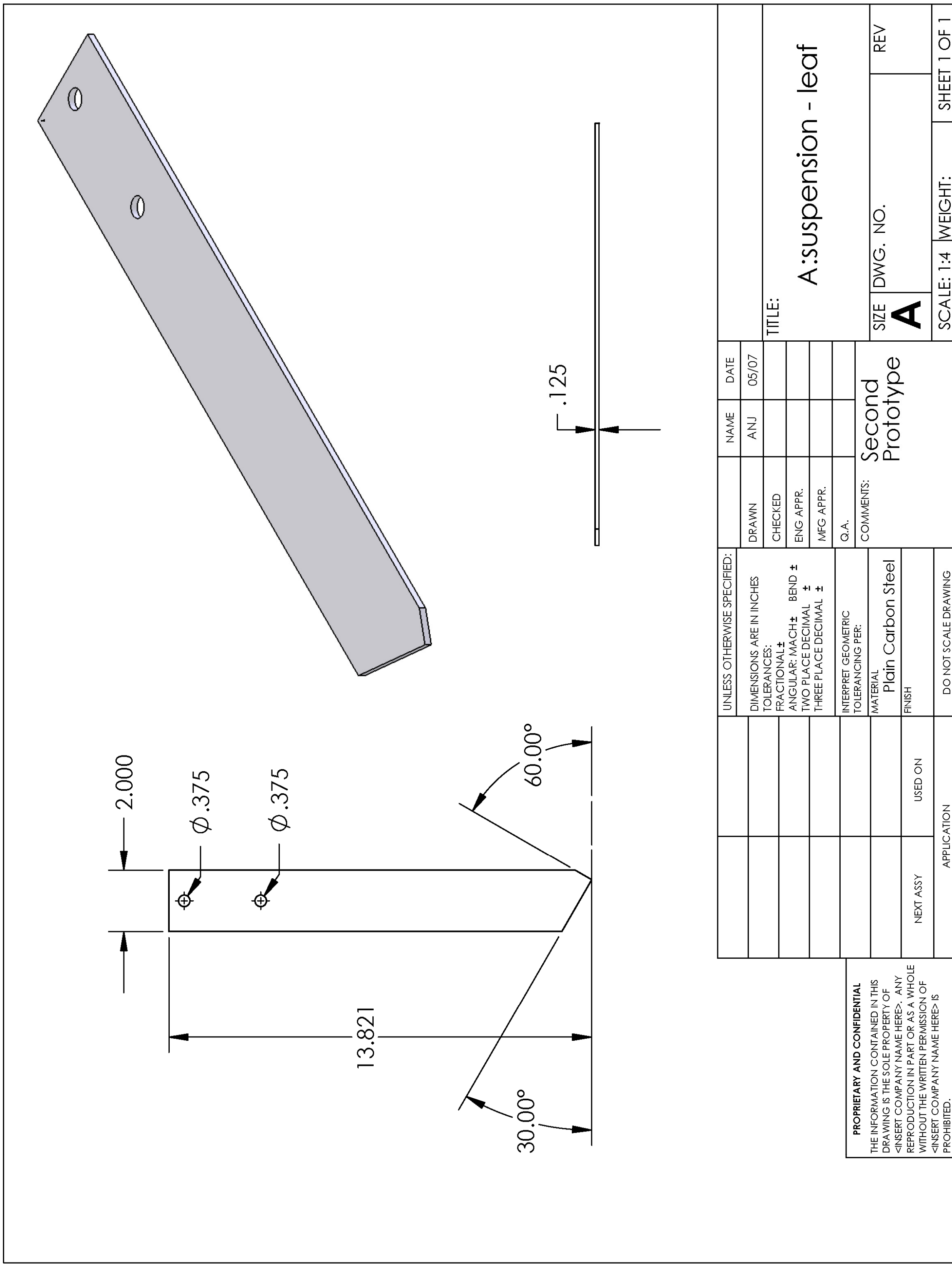
5
4
3
2
1



2.000
Ø.375
Ø.375
60.00°
13.821
30.00°
.125
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:suspension - leaf
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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5
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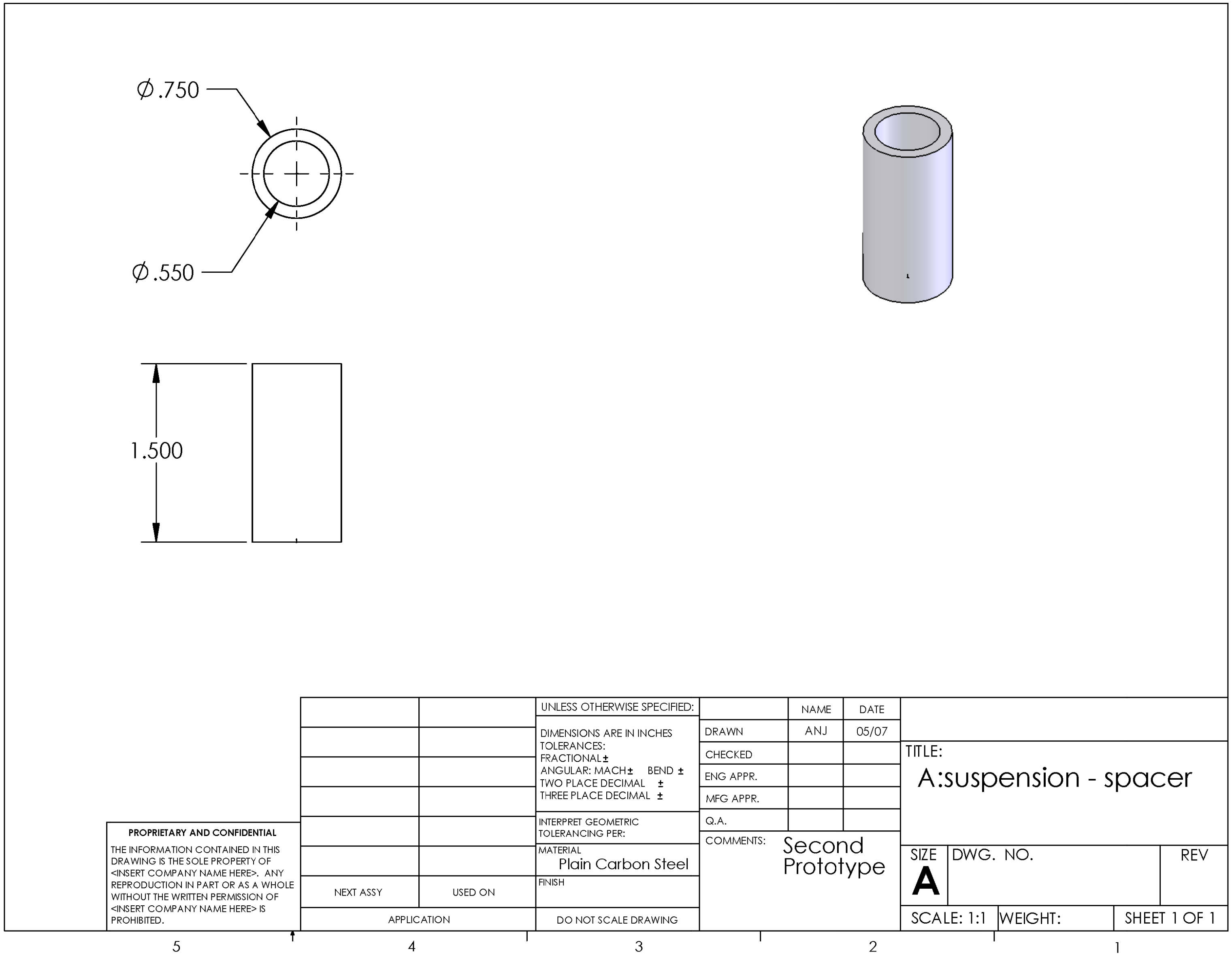
Ø.750
Ø.550
1.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
TITLE:
A:suspension - spacer
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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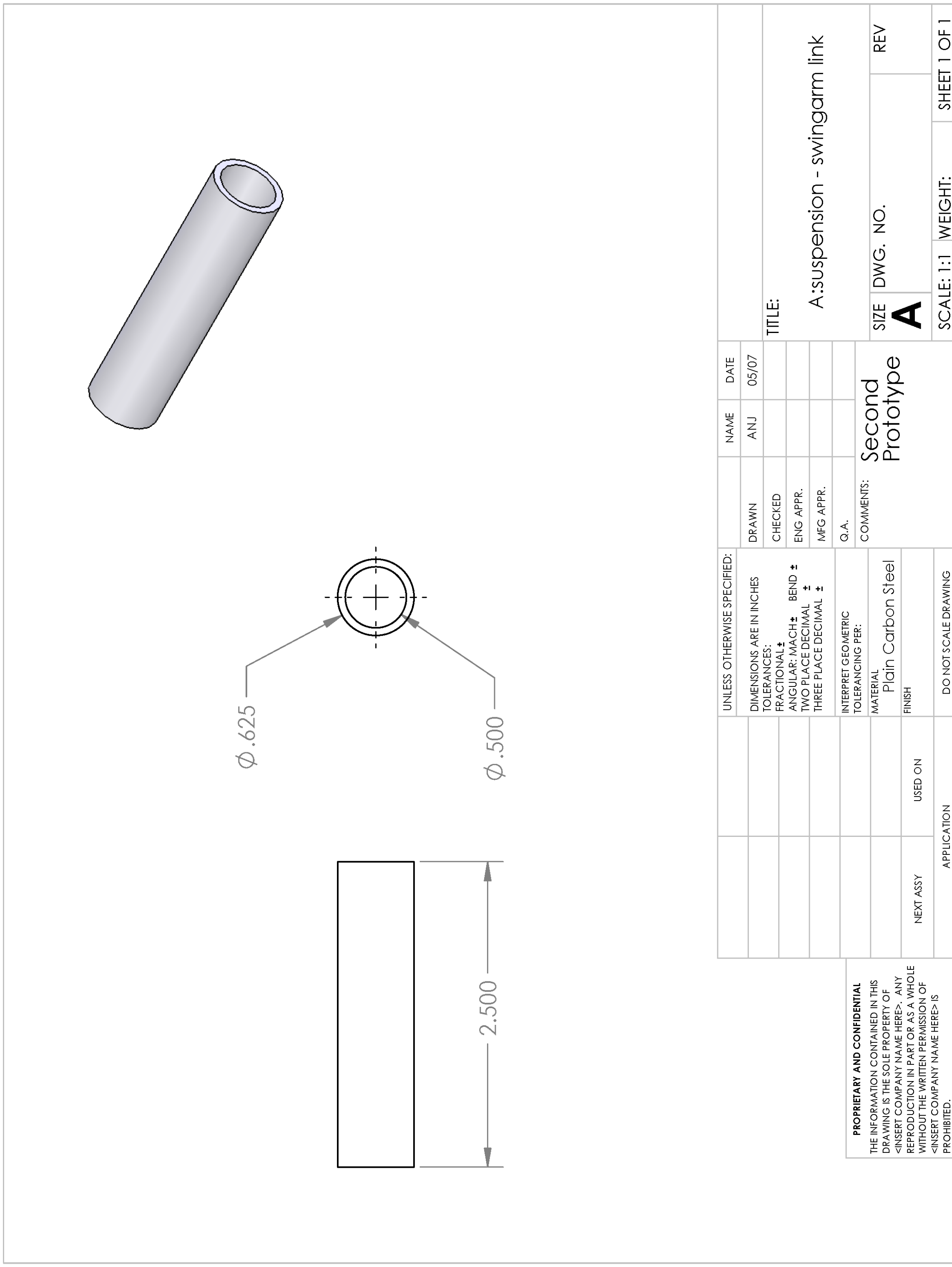
NEXT ASSY
USED ON
APPLICATION
5
4
3
2
1



Ø .625
Ø .500
2.500
PROPRIETARY AND CONFIDENTIAL
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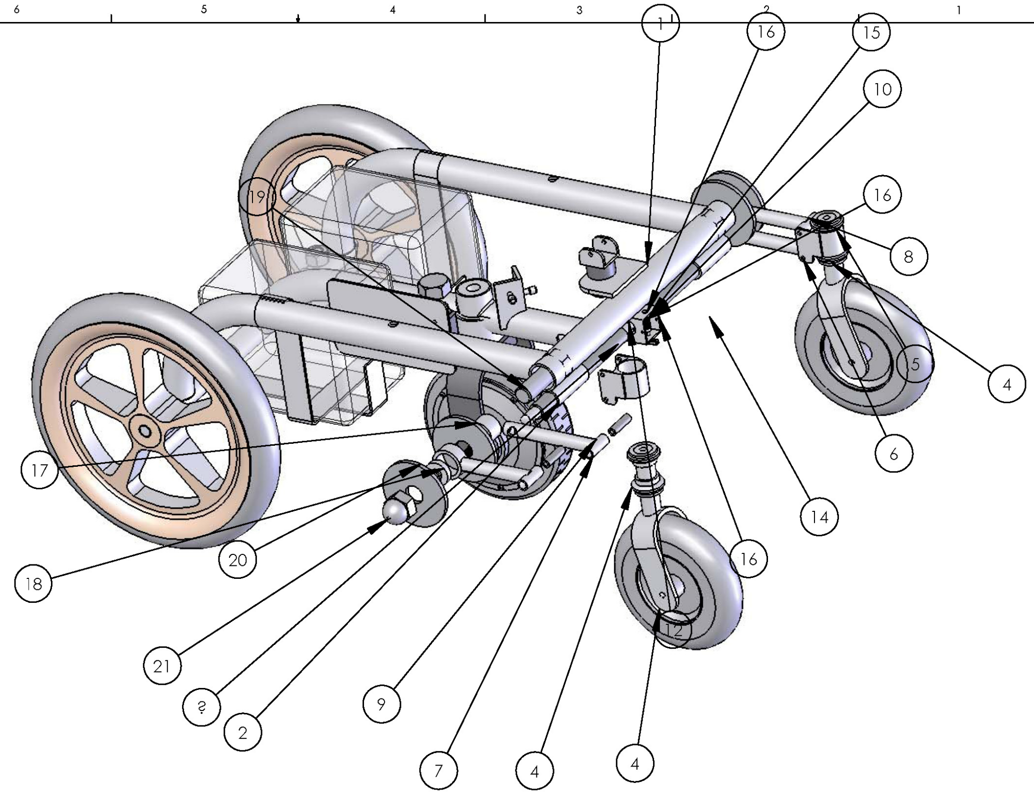
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Second Prototype
NAME
ANJ
DATE
05/07
TITLE:
A:suspension - swingarm link
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1

B.8 UPDATED SUSPENSION SYSTEM

One of the primary design issues discovered during the focus groups in India was the stability in the rearward direction. During steep uphill (especially on a side-slope) driving or during a sharp turn while going at a high velocity, the device could become unstable. A short-term solution to this problem was implemented before subject testing which effectively restricted the suspension travel and solved the stability problem. Unfortunately this solution also restricts the suspension system so the device does not functional optimally in rough terrain.

The mechanism for this instability is the same mechanism that allows for increased traction on the drive wheel during maneuvering in rough terrain. Because the leaf-springs act as a lever, transferring force from the caster to the center swing arm (to increase traction) the load is effectively transferred from a broad base of support (where the caster touch the ground) to the centerline of the device (where the leaf-spring attaches to the swing-arm). Load transfer at the leave-spring pivot point is also moved toward the midline (because of the angle of the leave spring) and thus reaction force of the leaf spring at the frame does not provide substantial anti-tip moments about the midline of the device.

ITEM NO.	PART NUMBER	QTY.
1	frame - cross back	1
2	frame - cross back fixed	2
3	frame - cross back fixed	1
4	caster fork assembly	2
5	suspension - caster barrel	2
6	suspension - linkage bushing	4
7	suspension - linkage barrel	4
8	swingarm - linkage bar upper	2
9	swingarm - linkage bar	2
10	frame - cross back bushing	1
11	frame - cross back bushing	1
12	frame - cross back insert	1
13	frame partial assembly	1
14	suspension - torque adjustment frame cover	1
15	gear	1
16	worm gear assembly 2	1
17	suspension - upper pivot sleeve	2
18	suspension - ball bearing	4
19	Hex Bolt_Al	2
20	Flat Washer Type A Selected Wide_Al	4
21	Acorn Low Crown Nut_Al	2
22	frame assembly	1
23	ground	1



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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

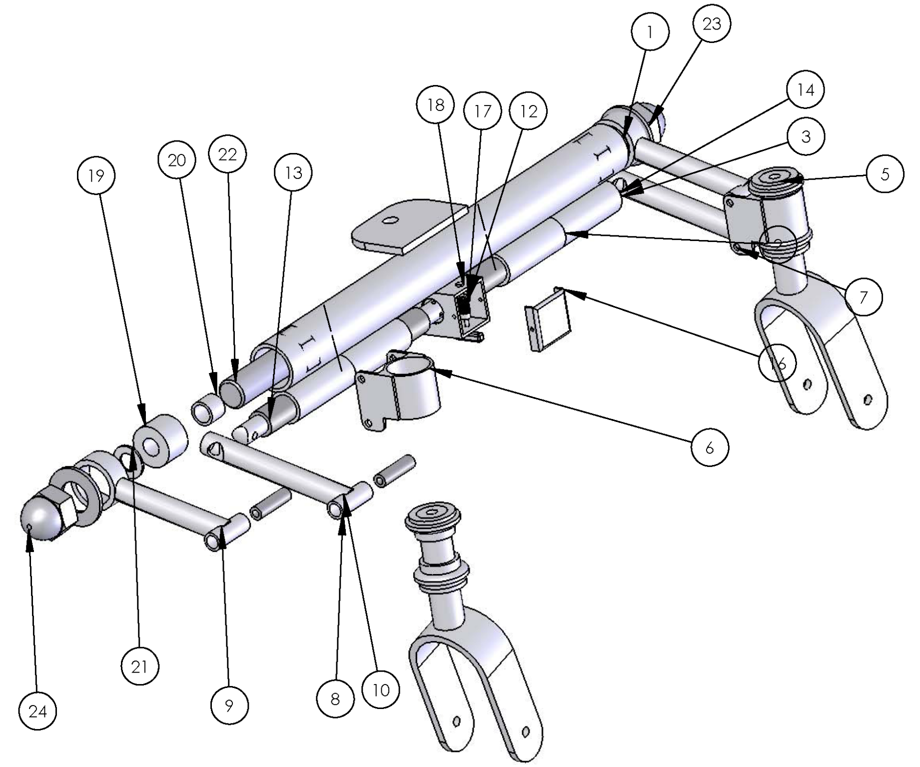
	NAME	DATE
DRAWN	ANJ	05/07
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
suspension assembly 2

SIZE B | DWG. NO. | REV
SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1

ITEM NO.	PART NUMBER	QTY.
1	frame - cross back	1
2	frame - cross back pivot	2
3	frame - cross back fixed	2
4	frame - cross back fixed	1
5	caster fork assembly	2
6	suspension - caster barrel	2
7	suspension - linkage bushing	4
8	suspension - linkage barrel	4
9	swingarm - linkage bar upper	2
10	swingarm - linkage bar	2
11	frame - cross back bushing	1
12	frame - cross back bushing	1
13	frame - cross back bushing	1
14	frame - cross back insert	2
15	frame partial assembly	1
16	suspension - torque adjustment frame cover	1
17	gear	1
18	worm gear assembly 2	1
19	suspension - upper pivot sleeve	2
20	suspension - roller bearing	2
21	suspension - thrust bearing	2
22	Hex Bolt_Al	2
23	Flat Washer Type A Narrow_Al	2
24	Acorn Low Crown Nut_Al	2



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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	ANJ	05/07
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

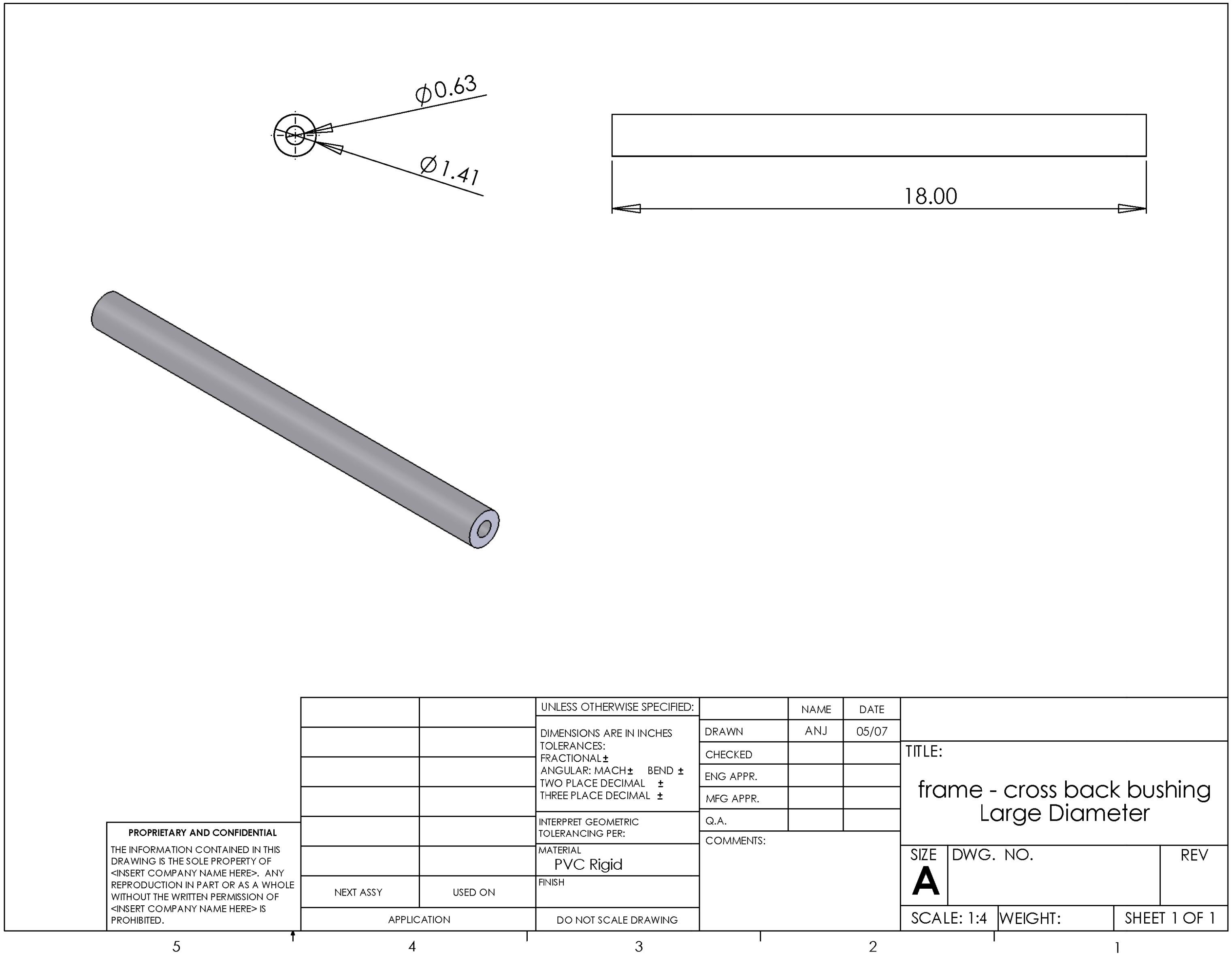
COMMENTS:

TITLE:

suspension assembly

SIZE B | DWG. NO. | REV

SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1



Ø0.63
Ø1.41
18.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PVC Rigid
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
frame - cross back bushing
Large Diameter
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
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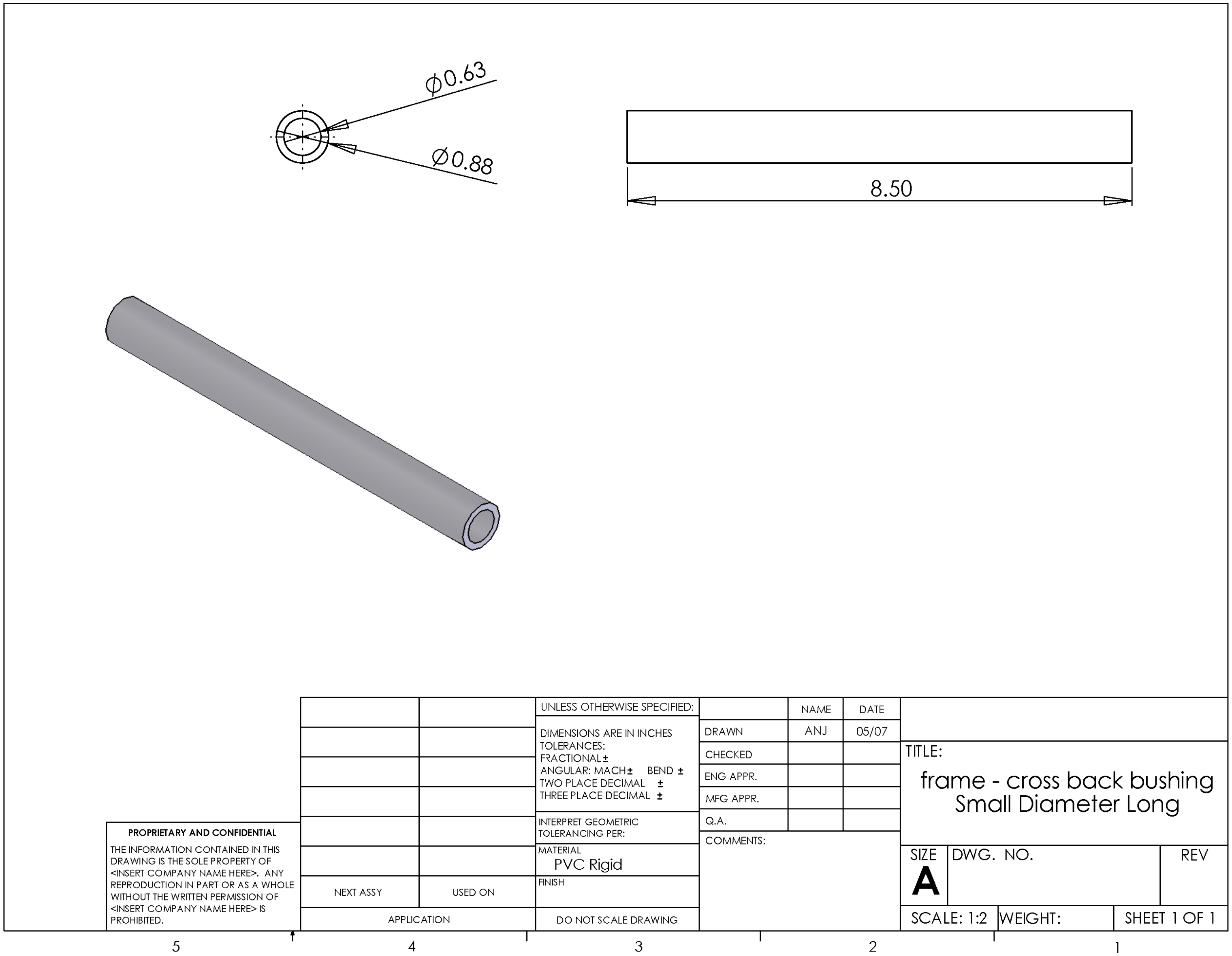
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Ø0.88
8.50
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TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
PVC Rigid
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
frame - cross back bushing
Small Diameter Long
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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NEXT ASSY
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APPLICATION
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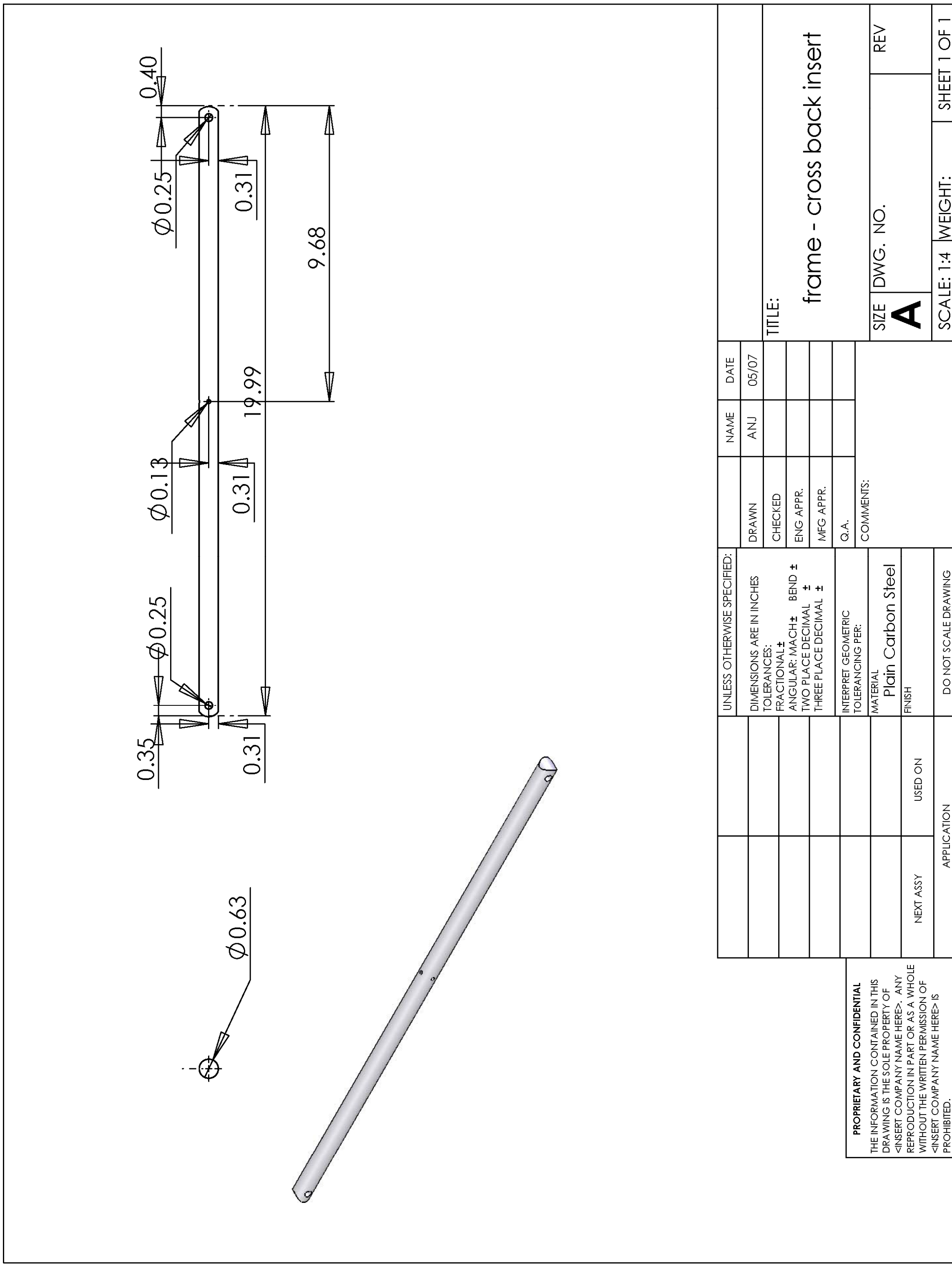

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9.68
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Ø0.13
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Ø0.25
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UNLESS OTHERWISE SPECIFIED:
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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
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USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
frame - cross back insert
SIZE
A
DWG. NO.
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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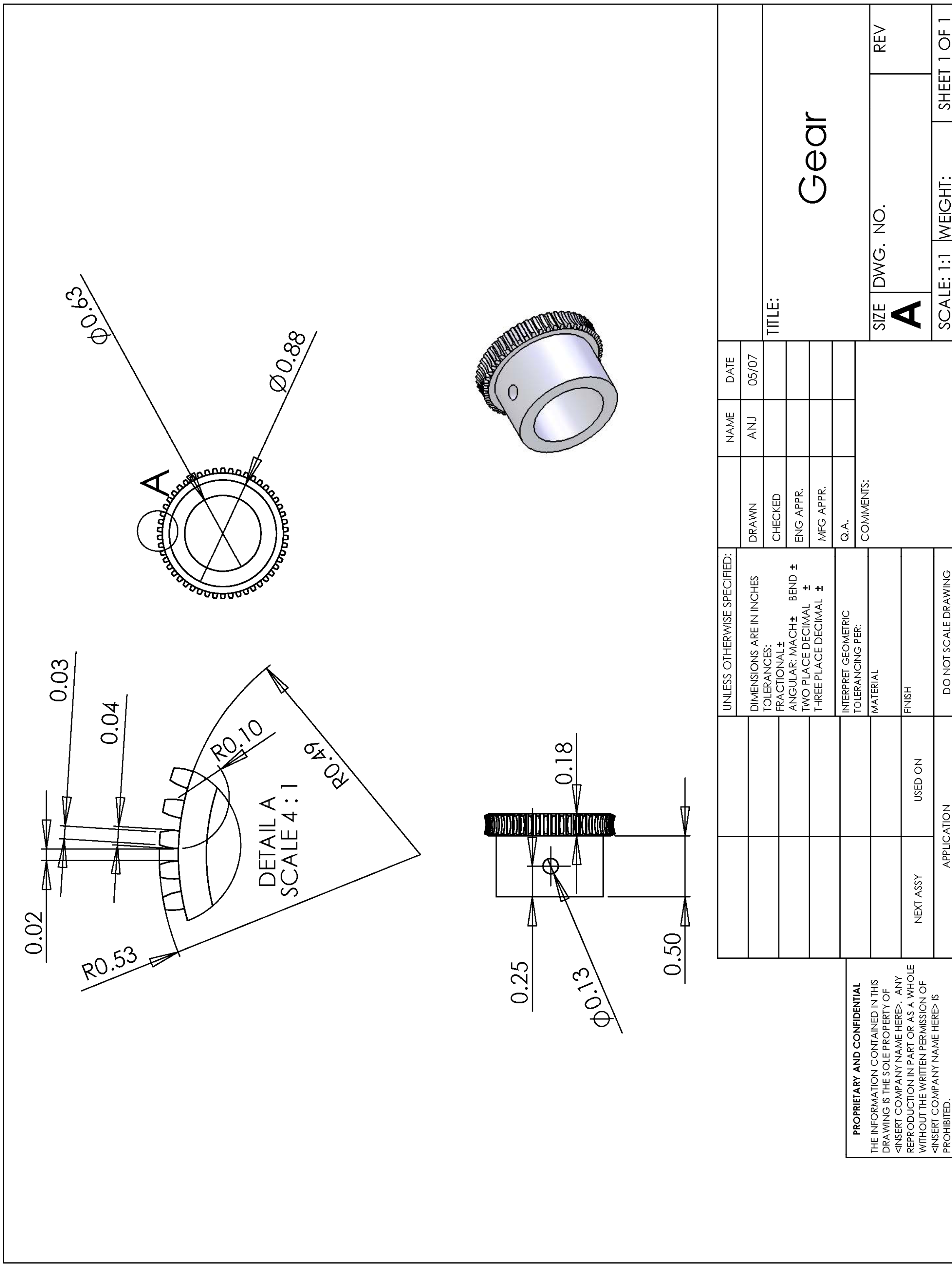
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R0.53
0.04
0.03
R0.10
R0.49
DETAIL A
SCALE 4 : 1
0.25
ϕ0.13
0.50
0.18
A
ϕ0.63
ϕ0.88
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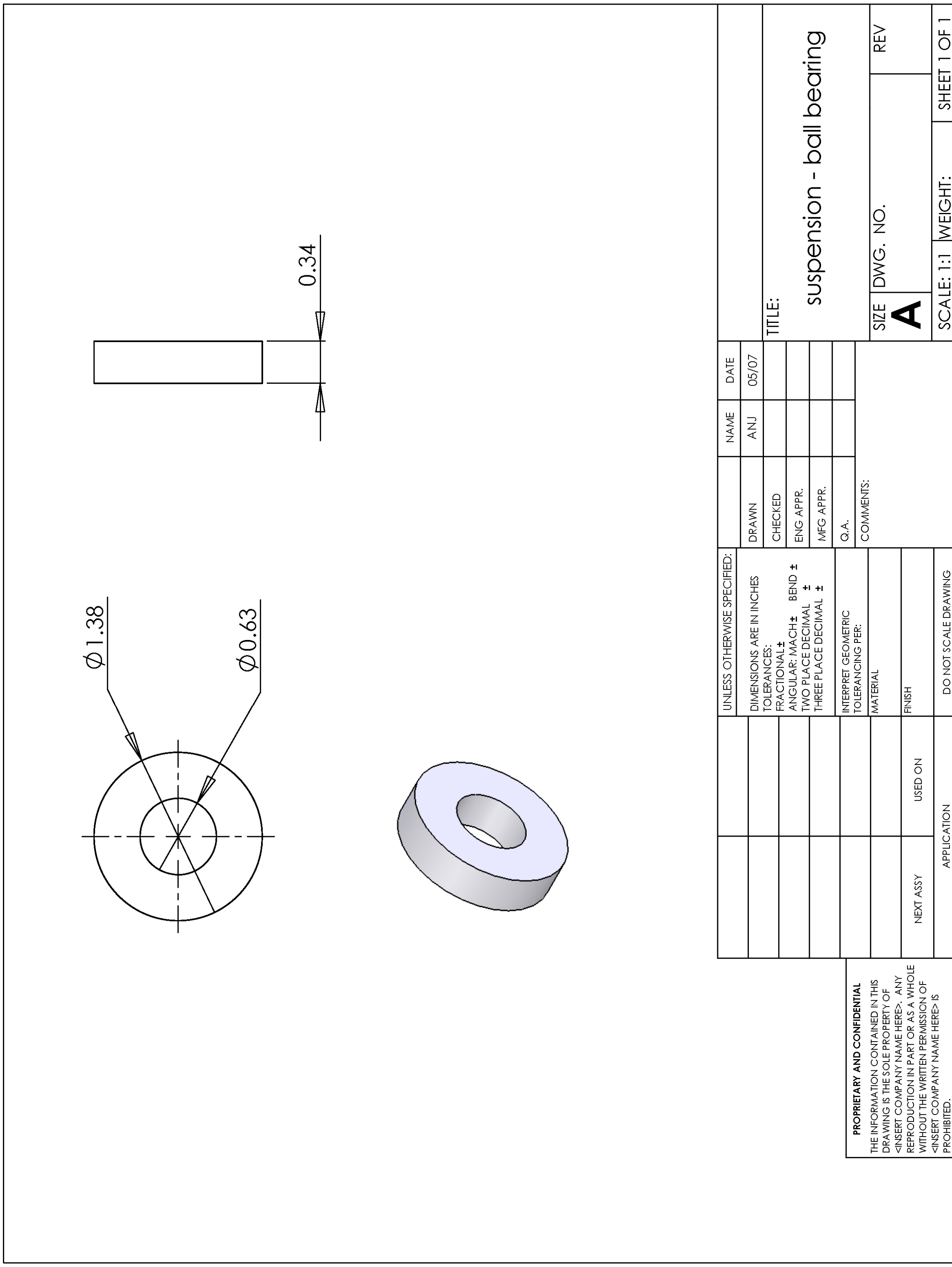
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Gear
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1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Ø0.63
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
suspension - ball bearing
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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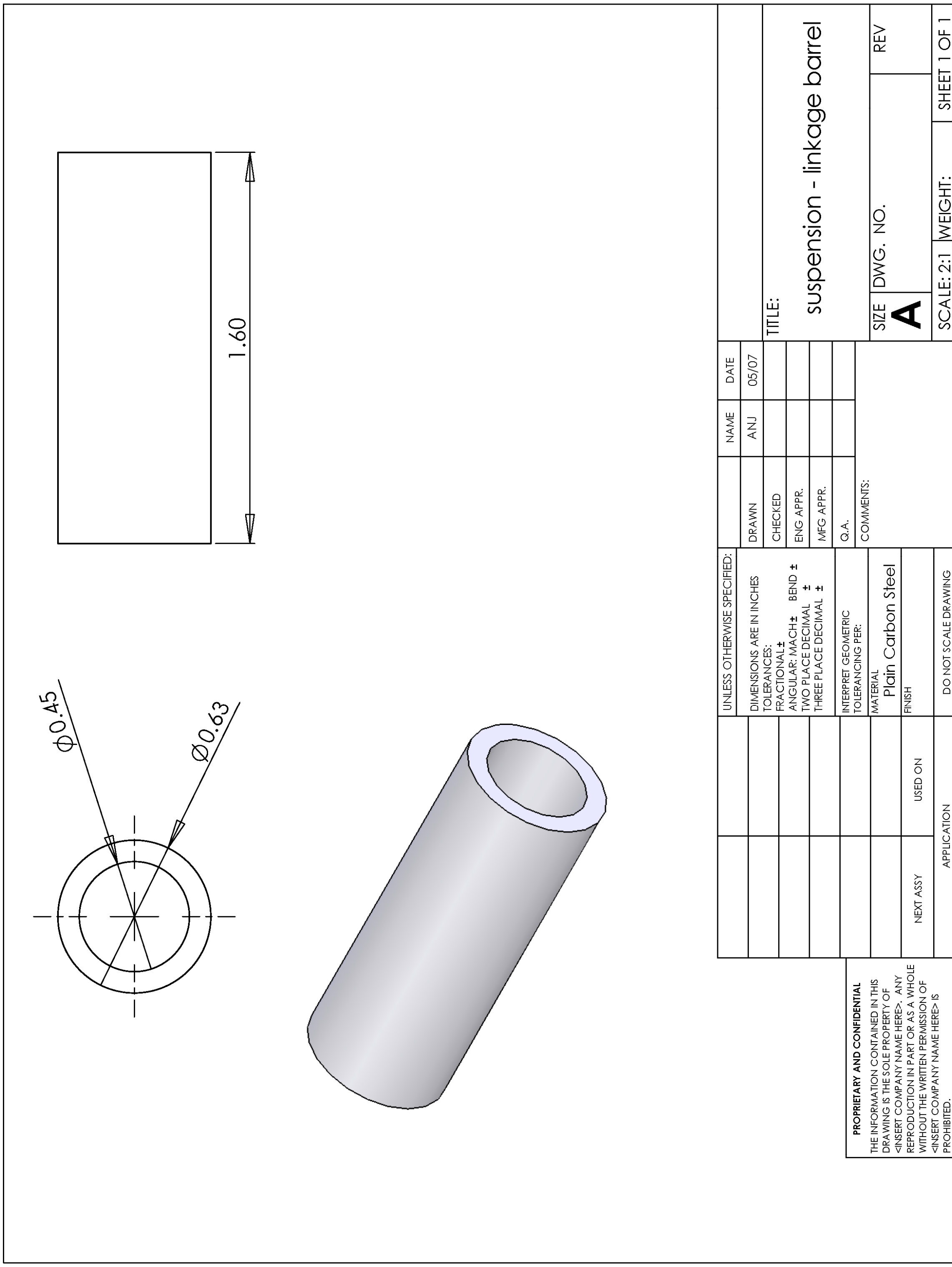

ϕ0.45
ϕ0.63
1.60
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
suspension - linkage barrel
SIZE
A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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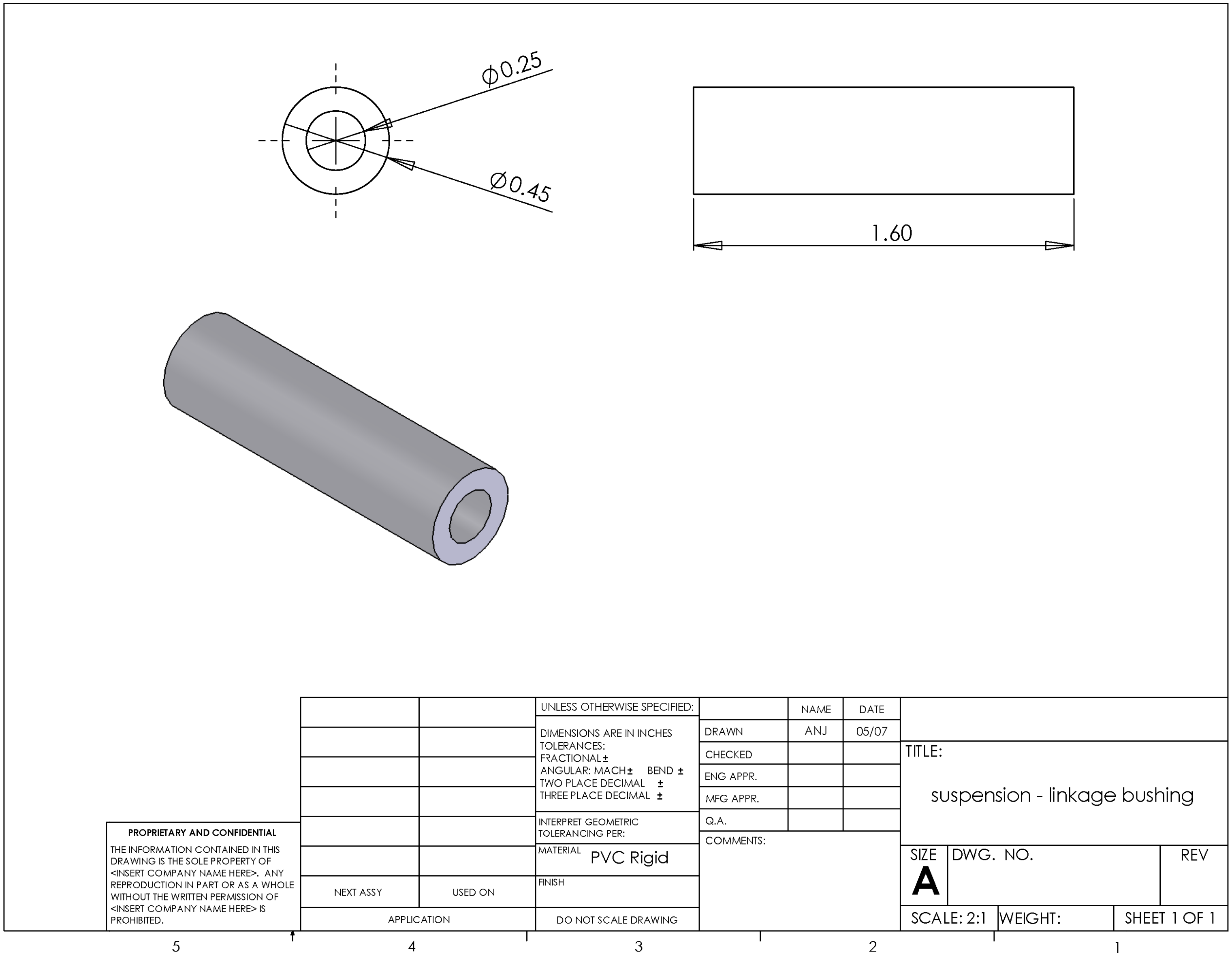
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Ø0.45
1.60
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL PVC Rigid
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN ANJ 05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
suspension - linkage bushing
SIZE A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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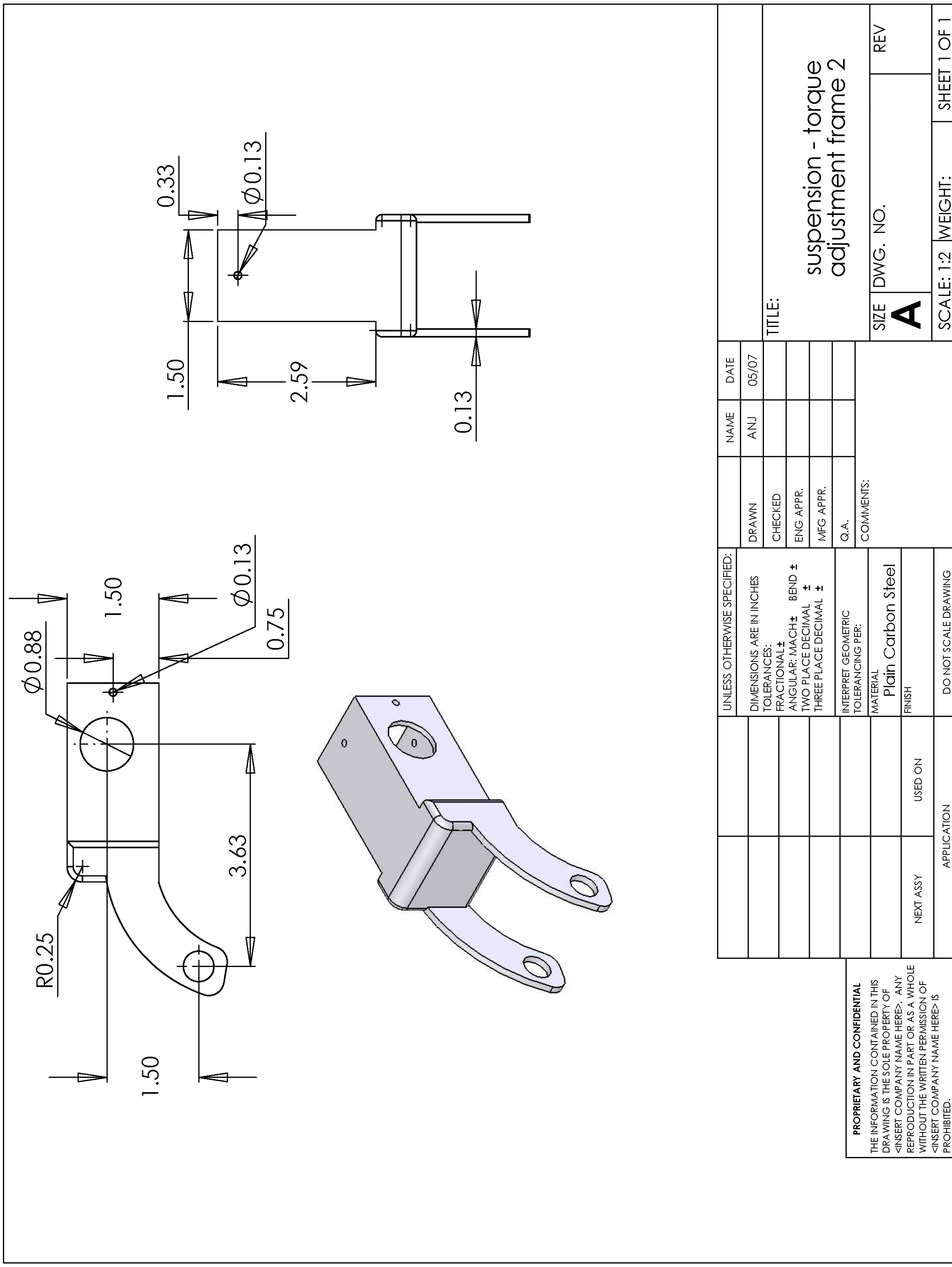
R0.25
Ø0.88
1.50
Ø0.13
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3.63
1.50
0.33
Ø0.13
1.50
2.59
0.13
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Plain Carbon Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ANJ
05/07
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
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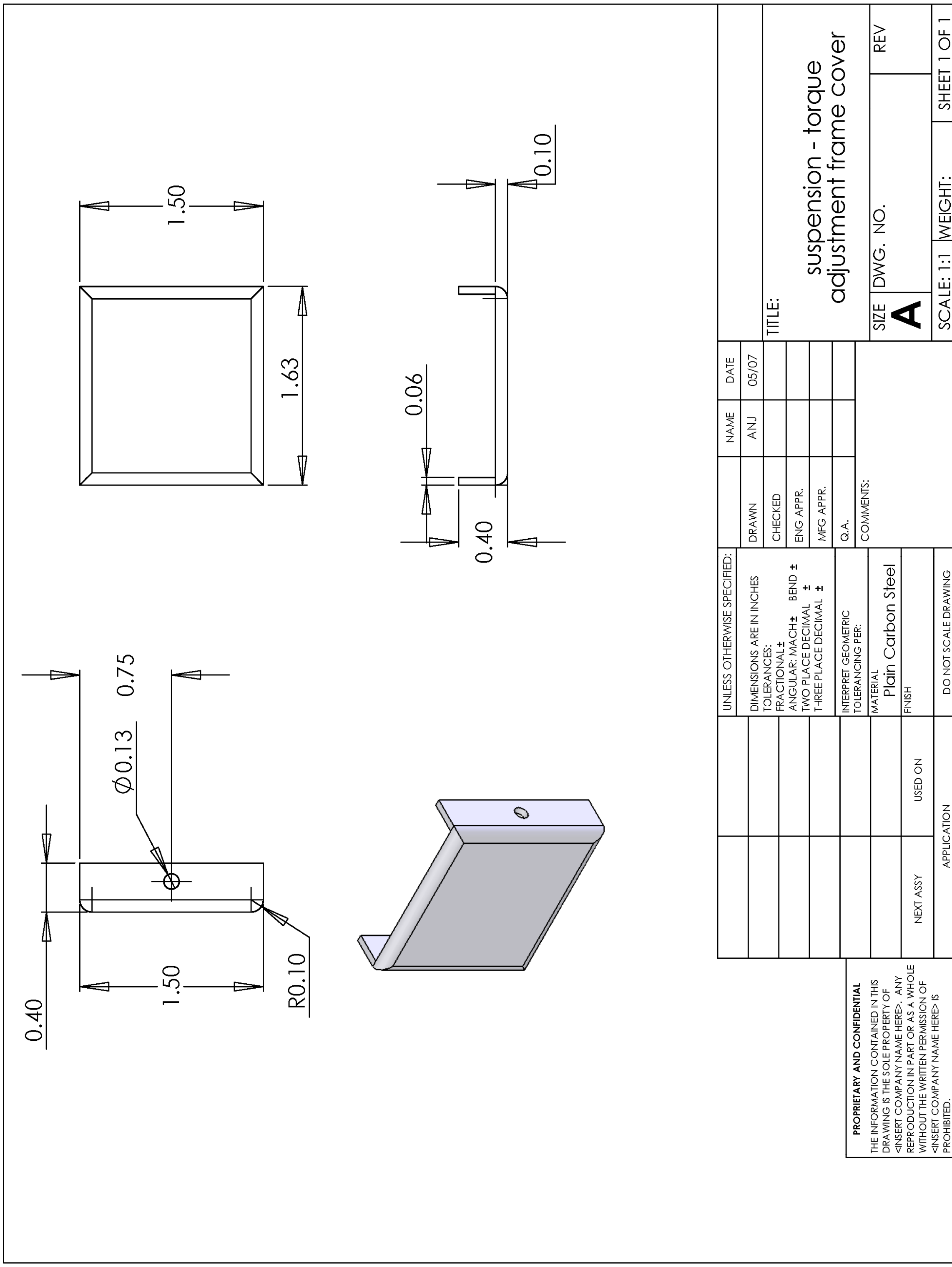

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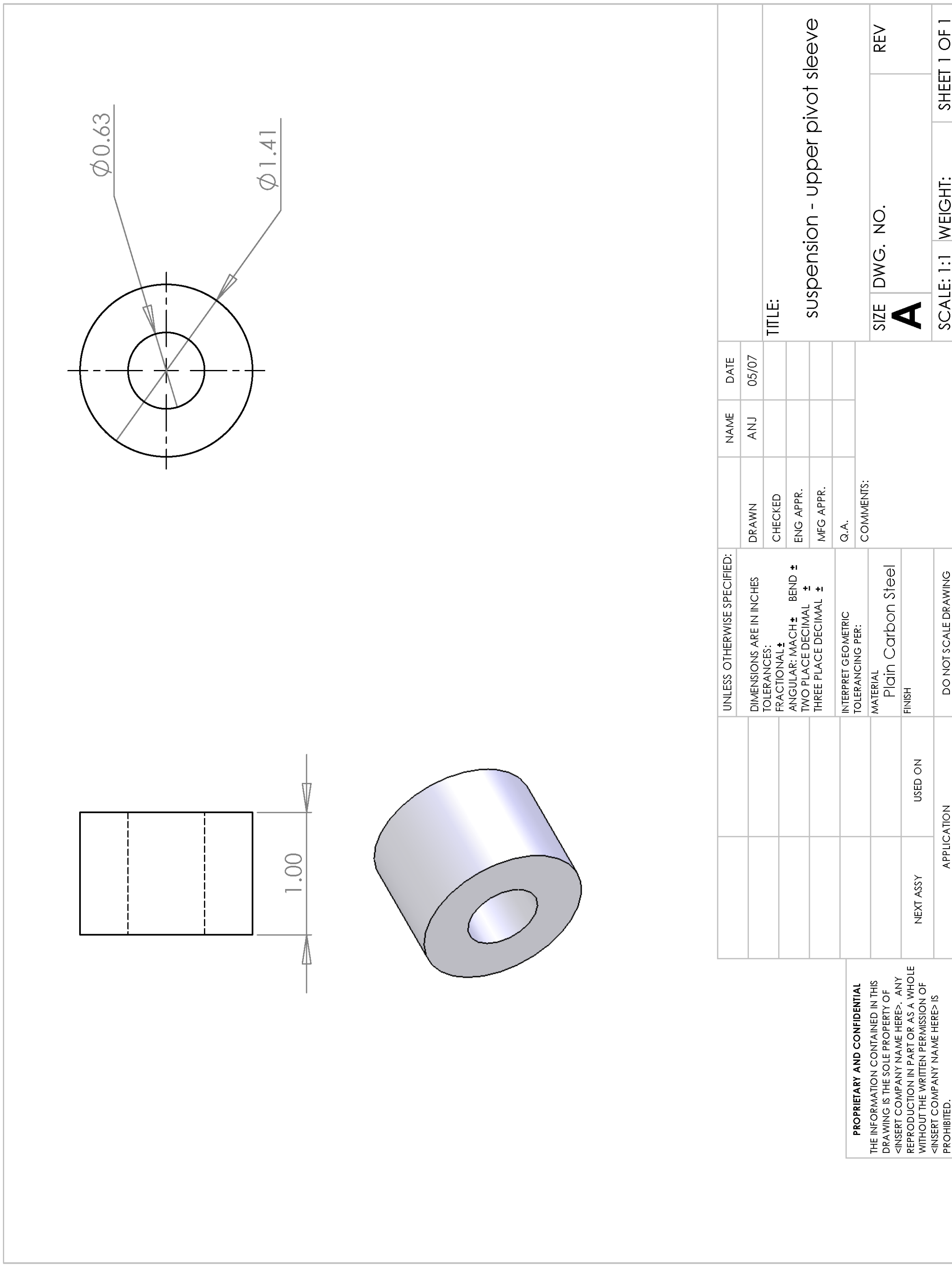
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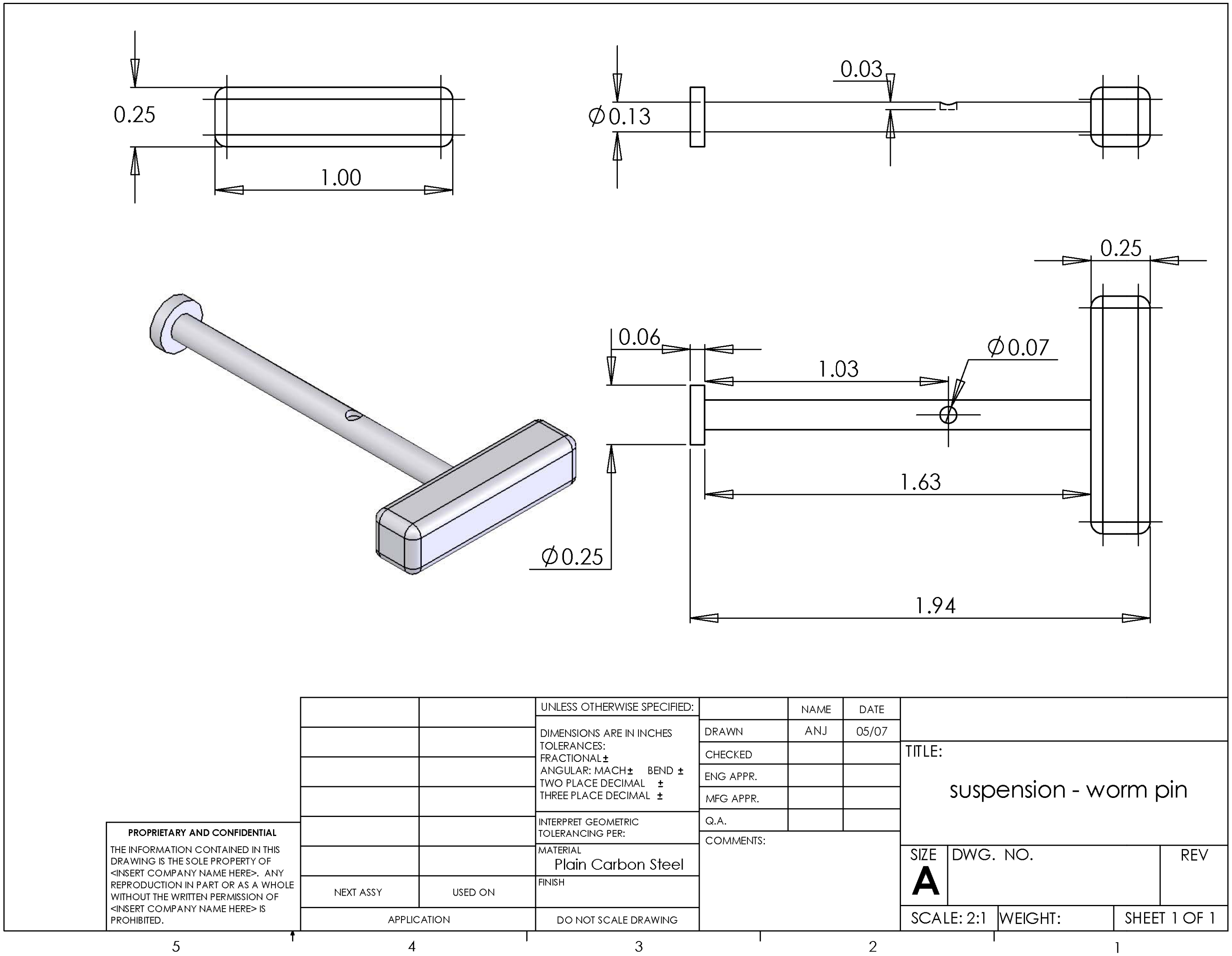
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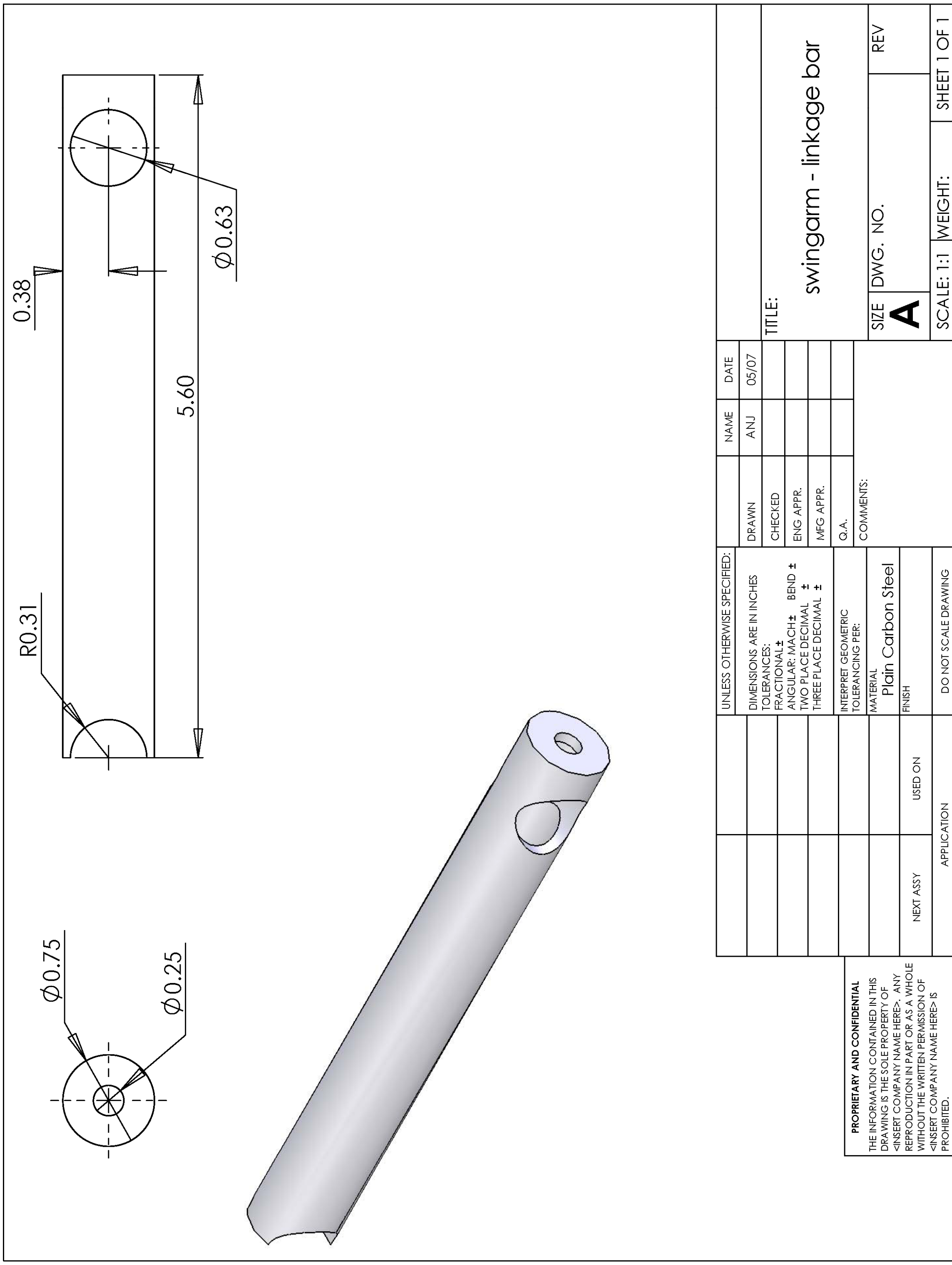
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COMMENTS:
TITLE:
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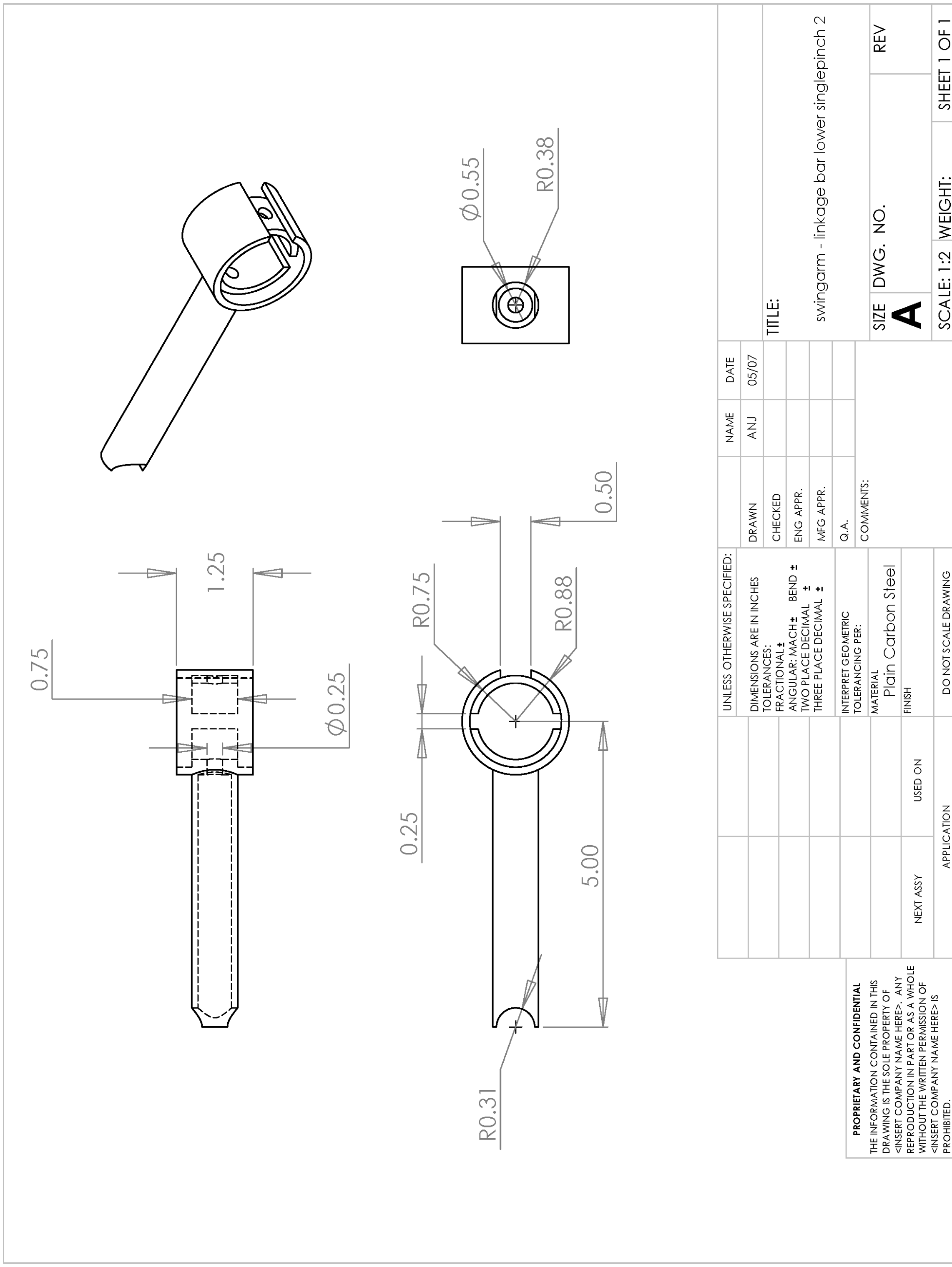
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COMMENTS:
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swingarm - linkage bar lower singlepinch 2
SIZE
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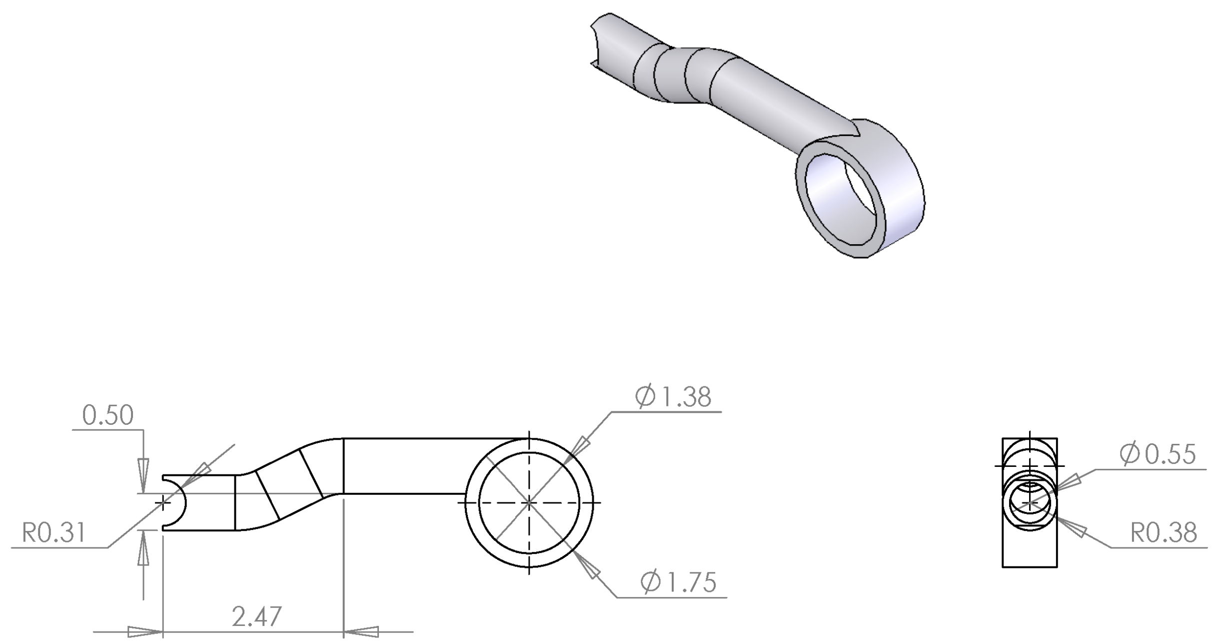

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	CHECKED			swingarm - linkage bar upper curved	
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MATERIAL Plain Carbon Steel	COMMENTS:			SIZE A	DWG. NO. / REV
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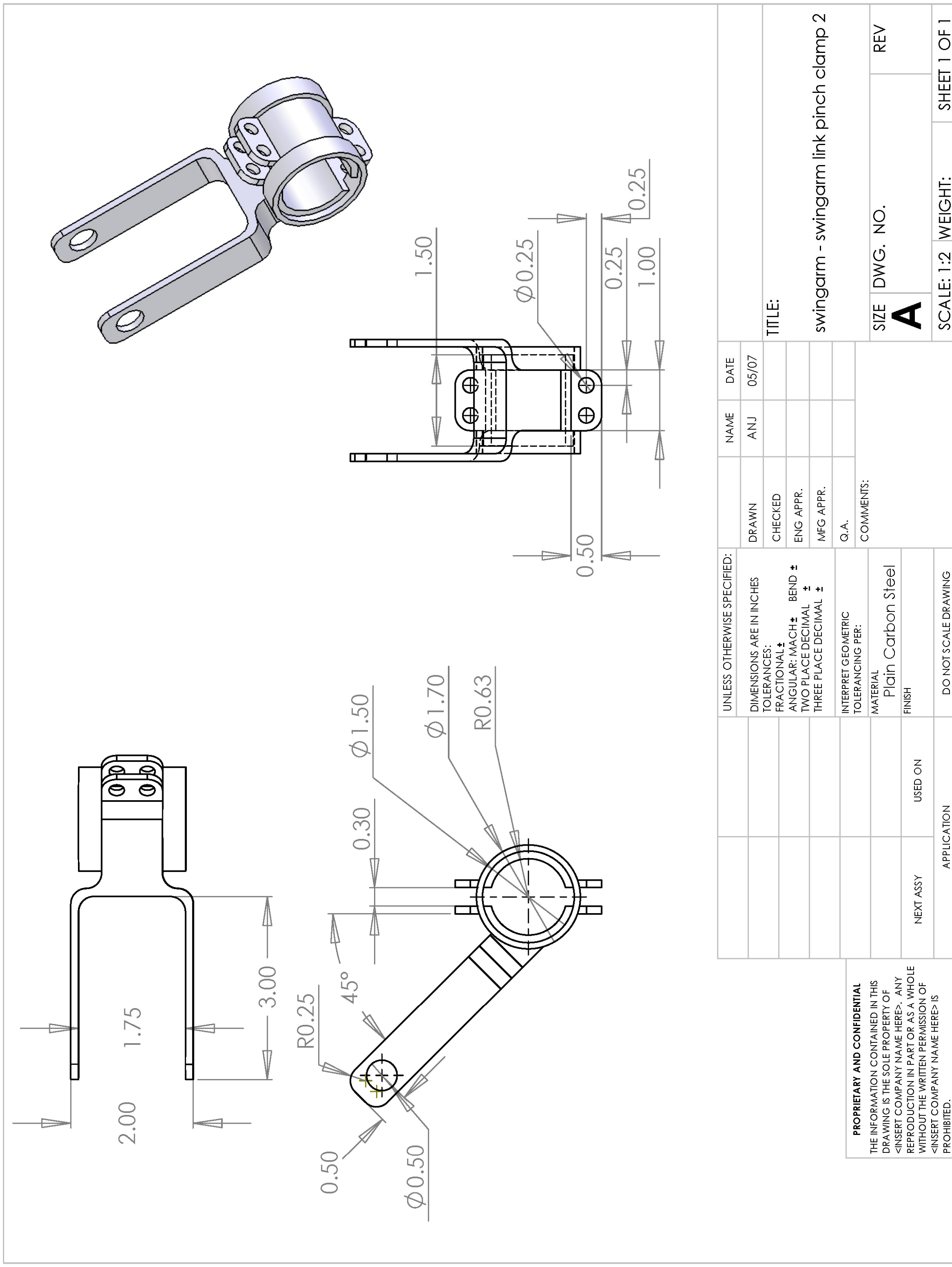

swingarm - swingarm link pinch clamp 2
TITLE:
SIZE
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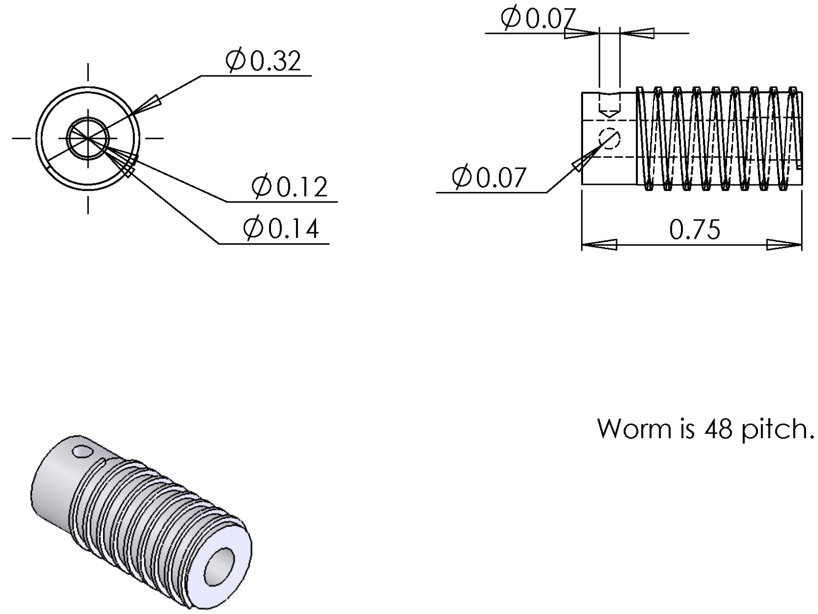

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INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
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COMMENTS:

TITLE:
WORM - 48 PITCHworm

SIZE A | DWG. NO. | REV

SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1

NEXT ASSY | USED ON
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B.9 OTHER SUGGESTED DESIGN CHANGES

Based on feedback from users, and also the general behavior of the device, several design changes could benefit the performance:

1) In the current design, there is nothing restraining the arm-rests from being flipped-up. Some users would have preferred to have a locking arm-rest, so they can pull against the arm-rest and tiller to re-adjust their torso. A locking system that could be easily un-latched (when they wanted to flip up the tiller and arm-rests) would benefit these users
2) The controller housing plant (currently place on the frame) could be re-located to the back of the batter-mounting straps. This would make the device more aesthetically pleasing from the side, and allow for a shroud to be placed over the frame-system.
3) The footrest should be redesigned to allow for separate support for each foot (rather than a centrally located single foot-rest). This would allow for patients with contractures and other complications to be fit more easily on the chair.
4) The tiller system, although works flawlessly, could have several design changes. First, a latching device could be added to secure the free end of the tiller housing to the arm-rest more rigidly. In combination with a latching mechanism on the arm-rest (as discussed above) this would make the whole tiller system more rigid, and would also be more useful to the user when trying to reposition themselves. The handle-bars should also allow for a steering device (such as a triple-pin control device, like used on automobiles) so that users will fine-motor impairment can steer the device.

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