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TM600 Telescopic Manipulator Add-On Product

A Design and Build Project

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Mechanical Engineering Technology
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Executive Summary

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Contents

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Glossary

Term	Definition
Factor of Safety	How much stronger a system is than it needs to be for an intended load
Failsafe Mechanism	A design feature to prevent damage to equipment or people in the case of failure.
Gear ratio	The ratio between the pinion gear and the gear
High carbon steel	Steel that has more than 0.3% carbon. It is stronger and more durable than low carbon steel
Modulus of Elasticity	A physical property of the material measures the resistance to being deformed elastically
Stress Concentration	A location in an object where stress is concentrated
Torsional Power	
Unified National Course	Threads to the standard of Unified Inch profile, in accordance with the Unified and American Screw Threads – ASA B1.1-1989.
Ultimate Strength	The point where maximum stress that can be applied long its axis before it breaks or weaken
Yield Strength	The point where maximum stress that can be applied along its axis before it begins to change shape

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Symbols

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Symbol	Meaning
Deg	Degree
E	Modulus of elasticity
ft	Feet
g	Gram
in	Inch
kg	Kilogram
lb	Pound
lb.in	Pound inch
N	Newton
N.m	Newton meter
psi	Pounds of force per square inch of area
rad	Radian
S_{UT}	Ultimate strength
S_y	Yield strength
T	Torque
W	Watt

Acronyms

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Acronym	Definition
FEA	Finite Element Analysis
FOS	Factor of Safety
RPM	Revolutions per Minute
UNC	Unified National Coarse

~~1.~~ 1 Introduction

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This document reports on the design, build, and testing of an add-on to the TM600 Telescopic Arm (TM600) developed for Med-Eng. The add-on consists of a linear actuator that will rotate the claw of the tool vertically.

Med-Eng is a leading manufacturer of protective equipment who specializes in ordnance disposal. They are considered a leading producer in their field and have been in business for over 35 years [1]. Their current specialty is producing protective suits, helmets, and ordnance disposal robots to ensure safety in the line of duty [1]. Med-Eng supplies protective equipment to over 100 countries, including Canada and the United States, and their products are widely used by both military and police departments [1].

The TM600 is a bomb disposal arm produced by Med-Eng that enables bomb disposal technicians to maximize their distance from target packages [2]. It is the latest generation of Med-Eng Telescopic Manipulators. Currently it is able to rotate 360deg on the Y-axis horizontally and extend up to 15ft [3]. The tool's range of motion is restricted by its inability to rotate upwards. In fact, few bomb disposal arms on the market allow for vertical actuation. This report provides an overview of the design and testing of an add-on that would correct this limitation by enabling the TM600 to actuate 90deg vertically. The add-on will increase the manoeuvrability of the TM600, particularly in tight spaces, thereby ensuring greater safety for the operator.

Med-Eng established specific design criteria for the product, which are listed below.

Major design criteria:

- The device must be able to rotate at least 90deg upwards
- The claw must still function as normal in any position and must remain in position if power is cut from the arm
- The add-on must be able to function as normal while carrying a 15lb load
- Guarding must be made to cover any additional pinch points in the add-on
- The add-on must fit into the pre-existing pelican case that comes with the TM600
- The device must be able to be easily installed to the TM600 without use of tools or without taking too much time
- The device must actuate the claw smoothly as to not shake the contents of the package
- The pre-existing power supply for the TM600 must be used
- The claw must still be easy to operate while the add-on is installed

Minor design criteria:

- The device must cost under $500 to manufacture and produce and must be able to sell for under $1000
- The parts used should primarily consist of parts already used by the TM600
- If fasteners are used, they should not be easily losable as the device is used mostly in the field
- Whatever parts possible should be manufactured using a 3D printer to save prototyping costs
- If possible, the add-on should be backwards compatible with TM600s that have already been produced.
- As few modifications as possible should be made to the pre-existing design

These criteria were incorporated into the final design, as will be discussed in later sections. Section 2 of this document will compare the different designs considered for the project and justify the chosen design. Section 3 will then provide a technical description and SolidWorks models of the final design, technical descriptions of the parts required for the add-on and a breakdown of the overall assembly.

Due to the unsafe nature of explosive devices, the bomb technician has to stay as far away as possible, that is why many militaries and police forces around the world have adopted to using the TM600 to dispose of suspicious packages [2]. The TM600 already saved countless lives globally, and sometimes by having one it can mean life and death for the technician. If 90deg of movement is added it will differentiate the TM600 from other similar products by giving its user more safety and control of the situation while still being able to easily manipulate a package.

Section 2 of this document will overview the different design ideas that were available for this project and will contain figures and tables detailing why that design was considered. Section 3 will provide a technical description of the final design as well as final SolidWorks models of the final add-on, technical descriptions of the new parts that are required for this add-on and breakdowns of the overall assembly.

~~2.~~ 2 Design Evolution

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The design process for this project has been based upon developing three major design ideas and evaluating them in accordance with the design criteria outlined in Section 1. Further, any additional considerations have been noted.

~~2.1~~ 2.1 Design 1 – Short Winch

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Design 1, as seen in Figure 2-1, utilizes a winch to pull the claw assembly through the 90deg rotation using the shaft through the claw assembly and telescopic arm fork as a pivot point.

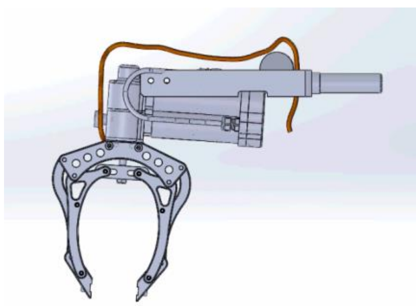

*Figure **Error! No text of specified style in document.**-1: Design 1 – Short Winch*

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~~2.2~~ 2.2 Design 2 – Worm Gear

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Design 2, shown in Figure Error**! No text of specified style in document.**-2 , utilizes a worm gear mounted to the side of the fork with the claw assembly mounted to the shaft of the gear train, enabling the rotation of the gears to actuate the motion of the claw assembly.

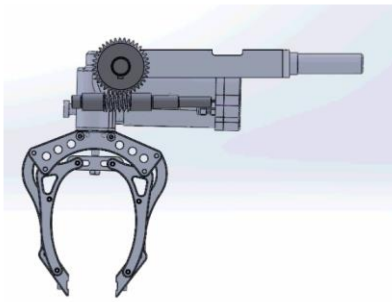

*Figure **Error! No text of specified style in document.**-2: Design 2*

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~~2.3~~ 2.3 Design 3 – Fork Winch

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Design 3 the Fork Winch, shown in Figure 3, utilizes a winch in a similar way to the first design except the entire fork assembly is rotated through the 90 degree motion, with a hinge added between the fork and the telescopic arm.

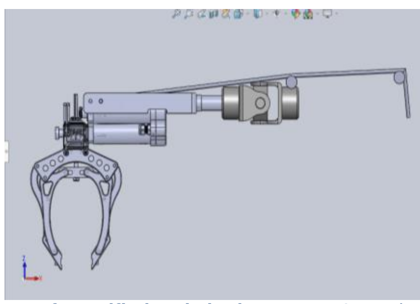

*Figure **Error! No text of specified style in document.**-3: Design 3 Fork Winch*

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~~2.4~~ 2.4 Comparison

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The tables below outline the criteria used to determine the most viable option, with the applicability to each design noted. Table i contains the analysis of the Primary Design Criteria, while Table ii contains the analysis Secondary Design Criteria.

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Table i: Primary Design Criteria Comparison

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Primary Design Criteria	Design 1	Design 2	Design 3
Ability to carry 15lb	Yes	Yes	Yes
Remain in position when power removed	Yes	Yes	Yes
Fit in iM3200	Possible	Possible	Uncertain
Actuate smoothly	Yes	Yes	Yes
Inexpensive	Yes	Yes	Yes

Table ii: Secondary Design Criteria Comparison

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Secondary Design Criteria	Design 1	Design 2	Design 3
Avoid small parts	No	Yes	No
3D Printable	Yes	Yes	Yes
Utilize existing power supply	Yes	Yes	Yes
Mimimal unique parts	Yes	Yes	Yes
Backwards compatible	Possible	Yes	Possible

When considering only the design criteria all three designs are equally viable. However, it is also necessary to account for risk. Design 1, the winch design, would require a great amount of housing in order to protect the cabling from being exposed which would introduce the risk of the cable snagging or simply becoming dirty and not functioning as intended. Additional housing introduces a level of complexity to the product that would be undesirable; further, it reduces the ease of backwards compatibility. Therefore, Design 2, the worm gear design, was chosen to be further developed.

~~2.5~~ 2.5 Chosen Design

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In order to design a suitable gear train to meet the torque requirements, an appropriately sized motor must be installed in the assembly.

A number of motors with planetary gear heads were considered and compared using gear train analysis. This analysis requires consideration of the effects of both the mass of the claw assembly and that of the 15lb package. Initially the claw assembly mass and centre of gravity must be assumed due to a lack of information. Additionally, it was assumed that the customer would prefer to utilize the current motor in the claw assembly. With these assumptions and a factor of safety of 2, the initial gear ratio was calculated at 80:1. In order to reduce the size of the worm gear, an additional stage was introduced to the gear train, this can be seen in Figure 2-4 below.

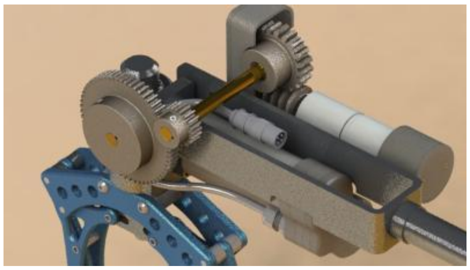

Figure ***Error! No text of specified style in document.****-4: Initial Design*

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In discussion with Med-Eng, the safety factor requirements are realized to be just 1.5, the claw assembly mass is approximately 25% of the assumed mass, and Med-Eng is open to utilizing a motor with a greater torque rating. These factors allowed for a design that required a gear ratio of only 27:1. The design developed for prototyping utilizes a motor/gear head with a 0.981Nm rating and a 30:1 ratio worm gear available from an off the shelf supplier. Figure 2-5 below shows this design within the proposed housing, which is much smaller than the original design seen in Figure 2-4 above.

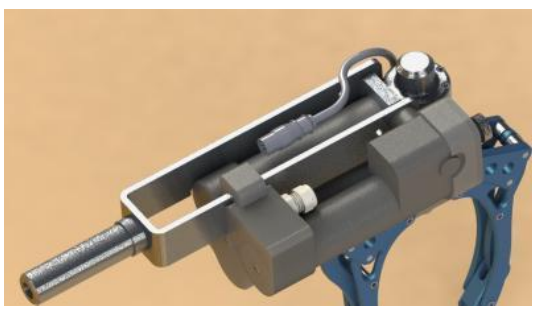

Figure ***Error! No text of specified style in document.****-5: Final Design*

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This design has undergone FEA analysis to ensure the existing TM600 can withstand the additional load, and has proven to be suitable. This design was developed into a complete prototype for physical testing in order to produce a fully functional add-on that will be ready for market in late 2019.

~~3.~~..3 General Description of the TM600 Add-On Product

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The TM600 Add-On product is a modular backwards compatible device enabling the actuation of the claw of the TM600 Telescopic Manipulator in a 90deg vertical motion (ie. “up and down”), dramatically increasing the usability of the TM600 itself. It is a user-friendly tool which is delivered to the customer assembled and requiring minimal steps for installation. Its modular construction promotes ease of transport, storage, installation and maintenance. Further, it is lightweight, requires minimal custom parts and is inexpensive to manufacture providing a valuable return on investment for the user.

The device is 70mm x165mm x 66mm overall with a shaft and bracket protruding a further 55mm, with a total weight of 495g. It clips onto the existing fork of the TM600 and is held in place by set screws. It is further secured by the actuating shaft which passes through both the fork and the claw assembly and is held in place by a thumb screw ensuring that the shaft does not move while in operation. Within the lightweight 57.5g housing, a motor and gear train mechanism rotates shaft and bracket causing the claw to rotate.

This section provides a part-by-part description of each major component and describes a cycle of operation. Figure Error**! No text of specified style in document.**-6 below shows the TM600 interfacing with the TM600.

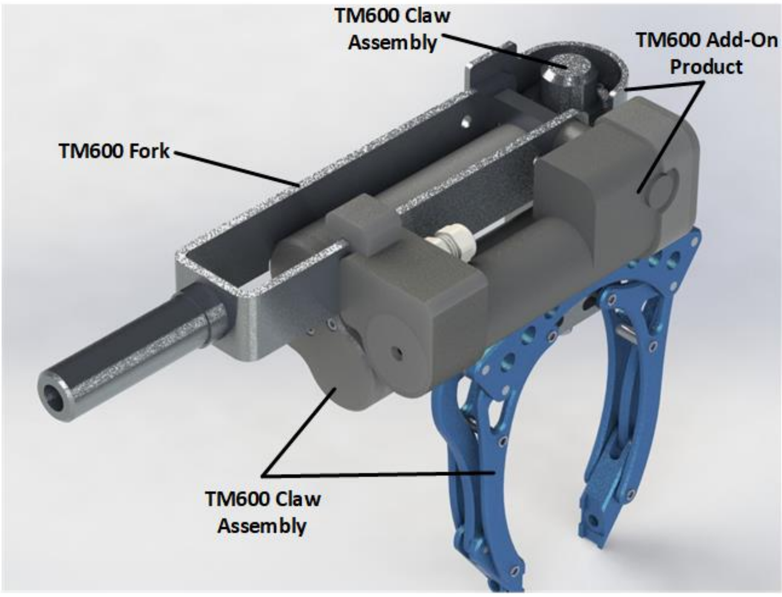

*Figure **Error! No text of specified style in document.**-6: TM600 with Add-On*

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~~3.1~~ 3.1 Part-By-Part Description of the TM600 Add-On Product

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The add-on product has been designed to be modular and consists of two major subassemblies. The Motor and Gear Train Assembly enables the actuation of the claw, while the Housing Assembly has two roles, firstly to mount the add-on to the TM600 telescopic manipulator, and secondly to provide protection to the Motor and Gear Assembly. Figure Error**! No text of specified style in document.**-7 below shows each of the components of the product.

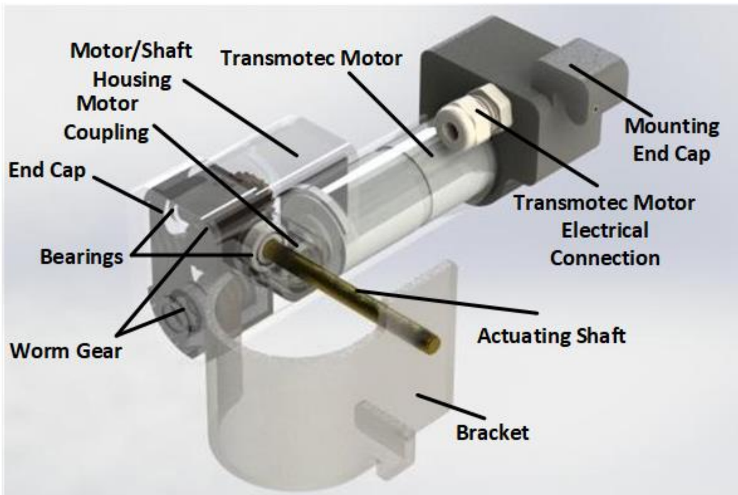

*Figure **Error! No text of specified style in document.**-7: Add-On Product Assembly*

~~3.1.1~~ 3.1.1- Motor and Gear Train Assembly

The Motor and Gear Train Assembly consists of all of the mechanical components required to provide the TM600 with the third degree of movement.

These components include:

- 12V Transmotec Motor & Electrical Connection
- Motor Coupling
- Worm Gear
- Actuating Shaft
- Bracket
- Bearings

Each of these components can be seen in Figure Error**! No text of specified style in document.**-8 and are utilized together to mechanically actuate the TM600 claw through a 90deg “up and down” motion. A thorough description of each component is found below.

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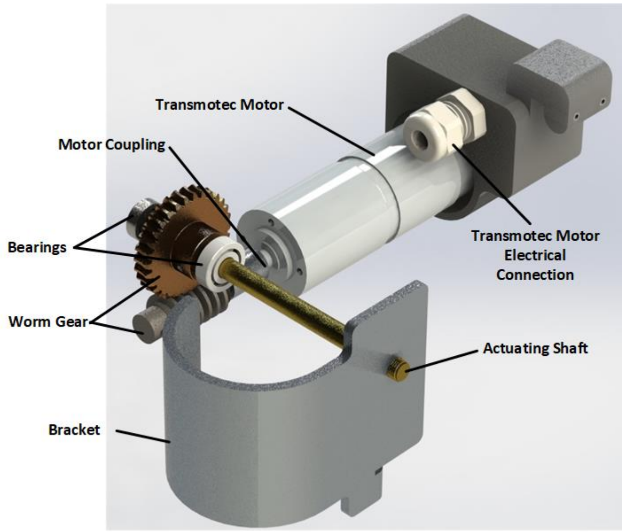

*Figure **Error! No text of specified style in document.**-8: Motor and Gear Train Assembly*

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~~3.1.1.1~~ 3.1.1.1 Transmotec Planetary Gear Motor

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The Transmotec PD2846-12-264-BF Motor provides the driving mechanism for the entire product. It consists of a 12V DC motor and a planetary gear head and is powered by the 12V DC power source existing within the TM600, the electrical cable is threaded through the Mounting End Cap and has. It has a diameter of 28mm, length of 90.3mm, torque rating of 0.981Nm [1], and weight 0.2kg. A shaft protrudes from the motor housing as seen in Figure Error! **No text of specified style in document.**-9, this drives the Motor Coupling and ultimately the entire gear train.

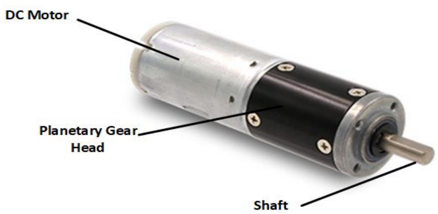

*Figure **Error! No text of specified style in document.**-9: Transmotec PD2846-12-274-BF*

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~~3.1.1.2~~ 3.1.1.2 Motor Coupling

The Motor Coupling is a 2g high carbon shaft which is hollow at one end to enable mating of the Transmotec Motor and keyed at the other to allow a worm pinion to be mounted to it. It is a component which serves to transmit power from the motor to the Worm Gear and to connect the two components. The coupling is mounted to and rotated by the motor shaft, causing rotation of the worm gear, transferring the motor's rotation to the gears. The worm is mounted to the Motor Coupling and secured with a set screw. The coupling is made of high carbon steel with an overall length of 43.12 mm. It is connected to the motor via a keyed cylinder, with an outer diameter of 11.08mm, an inner diameter of 5mm, and length of 16.54mm, as seen in Figure Error! **No text of specified style in document.**-10. A tapped hole with 4-40 UNC is located 32.98 mm from the bottom of the hole; this hole secures the connection of the motor and coupling together.

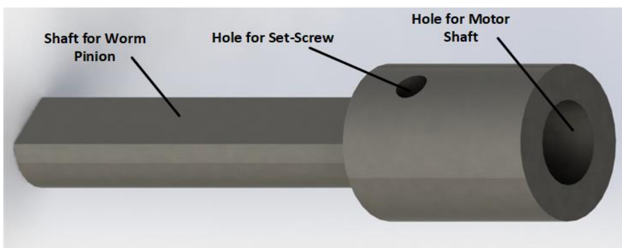

*Figure **Error! No text of specified style in document.**-10: Motor Shaft Coupling*

~~3.1.1.3~~ 3.1.1.3 Worm Gear

The worm gear is a mechanical device that consists of a threaded shaft which is called worm gear, which is meshed together with a spur gear. When the worm gear rotates it transfers its rotation to the spur allowing for torque to be shifted to a perpendicular plane.

The worm is mounted to the motor coupling and is driven by the motor; it is made out of hardened carbon steel, has a pressure angle of 14.5deg [3], and is right-hand drive. The spur gear is made from commercial bronze and also has a pressure angle of 14.5deg. There exists a gear ratio of 1:30 between the worm and the spur gear; this gear ratio increases the torsional power of the motor from 0.981Nm to 25.43Nm [4] and reduces the speed of rotation to 0.39RPM. The spur gear is mounted to the actuating shaft and is what drives the shaft through its rotation. The spur gear weighs 110g while the worm weighs 20g. Figure Error! **No text of specified style in document.**-11 shows the meshed gears and all the features explained above.

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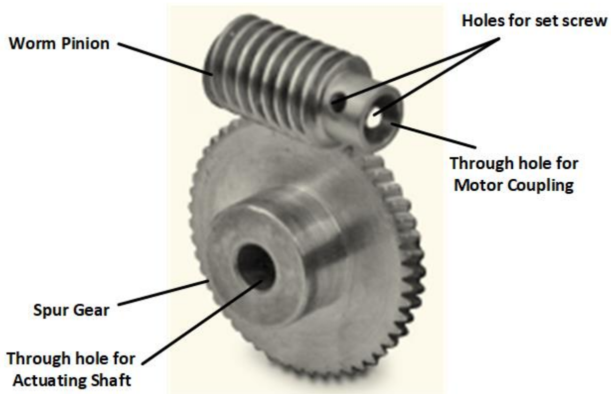

*Figure **Error! No text of specified style in document.**-11: Worm Gear and Spur Gear*

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~~3.1.1.4~~ 3.1.1.4 Actuating Shaft

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The Actuating Shaft is a high carbon steel rod with one end keyed to enable a gear and two bearings to be mounted to it, the other end is threaded and keyed to allow for both the Bracket and a thumbscrew to be utilized and is press fit into the claw assembly to actuate the claw. The shaft is 21.5g, 105mm long, and has a major diameter of 6.35mm and a minor diameter of 5mm. It has a flat keyway that is 10mm long on the 5mm diameter end. The other end is threaded to 5mm UNC ¼-20 and is keyed to enable the attachment of the Bracket. It is designed to be press-fitted into the 6.35mm bored hole in the TM600 claw assembly which enables the claw to actuate: as the shaft rotates the claw is forced to move in the same direction. The characteristics of the Actuating Shaft can be seen in Figure Error**! No text of specified style in document.**-12.

The shaft is mounted to the bearings and spur gear and passes through the TM600 fork and claw assembly, and the Bracket. The spur gear is mounted on the keyed end while the threaded end of the shaft passes through the claw. The threaded end is covered by a thumb screw to prevent the assembly from slipping during operation.

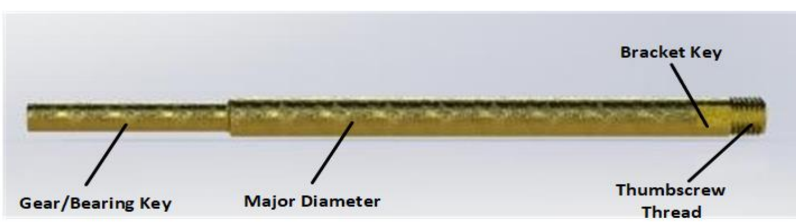

*Figure **Error! No text of specified style in document.**-12: Actuating Shaft*

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3.1.1.5 Bearings

~~3.1.1.5~~

A ball bearing is composed of three parts: the external race, the balls and the internal race. A bearing reduces friction by fixing the external race and leaving interior bearing race free to rotate; the balls between each race reduce the friction between the two rotating elements.

Two ball bearings are press-fit within the Motor/Shaft Housing with the Actuating Shaft press-fitted to the internal race which reduces friction during use; this installation can be seen in Figure Error! **No text of specified style in document.**-13. The bearings have a secondary role, they support the load of the claw assembly which reduce stresses on the shaft.

Each 5g bearing is permanently lubricated with a 0.1875in inner diameter and 0.5in outer diameter and face-width of 0.196in [2]. They are dustproof and waterproof to prevent contamination of the gear train promoting a long product life.

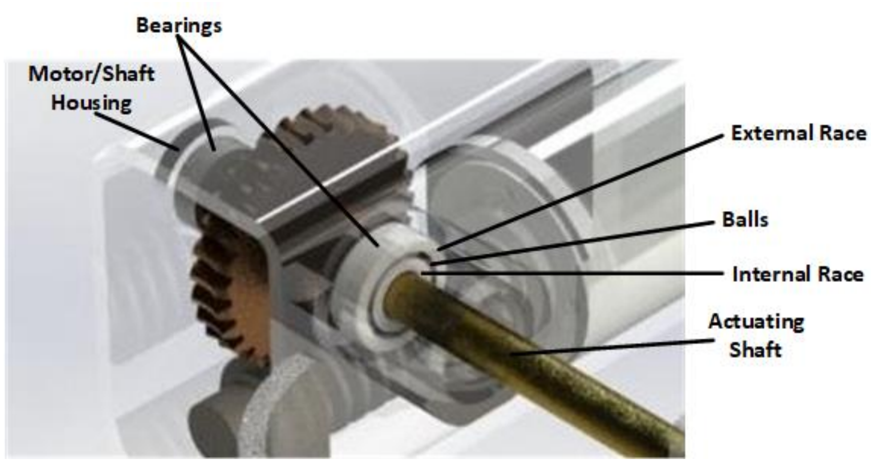

*Figure **Error! No text of specified style in document.**-13: Ball Bearing Installation & Features*

~~3.1.1.6~~ 3.1.1.6 Mounting Bracket

The Mounting Bracket is a formed piece of sheet metal with one end rolled to fit around the shaft of the TM600 claw, and the other end bent to fit around the back of the claw. It is used to support the claws weight during actuation and acts as an additional failsafe mechanism. It is mounted to the Actuating Shaft on the outside of the fork, between the

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fork and the thumb screw. It then clips around the outside of the claw assembly, ensuring safe actuation of the claw. Figure Error! No text of specified style in document.-14 shows the mounting of the bracket.

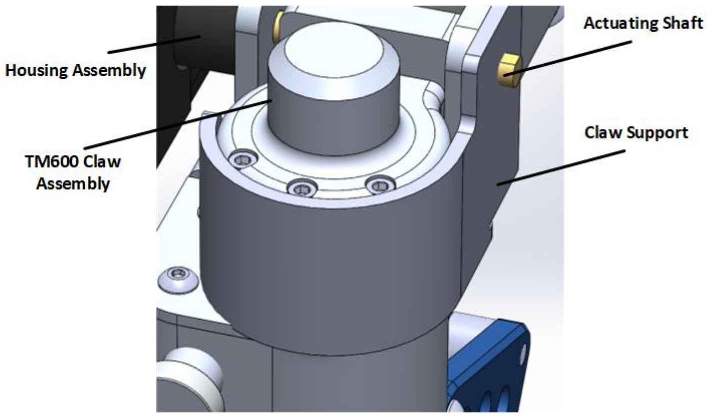

*Figure **Error! No text of specified style in document.**-14: Mounting Bracket*

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The bracket is made of 0.125in carbon steel sheet and is laser cut, bent, and rolled to support the claw assembly fully. It has a total weight of 145g, and is 40mm wide x 55mm long x 100mm tall. The main claw support is rounded to a radius of 0.9in to fit flush to the outside diameter of the claw assembly. There exists a keyed hole which mates with the actuating shaft as seen in Figure 3.1.1.6.2; the keyed design ensures that when the actuating shaft rotates the bracket does the same. Since the bracket is not dependent on a press fit it provides an additional safety feature as if the shaft were to slip within the claw itself, the bracket will still enable the claw to actuate. Finally, the rear claw support is bent with a 0.125in radius and sits against the claw assembly pushing upwards, and providing an additional resting place for the assembly when not in motion or when returning to the downwards position. Figure Error! No text of specified style in document.-15 below shows each of these individual features.

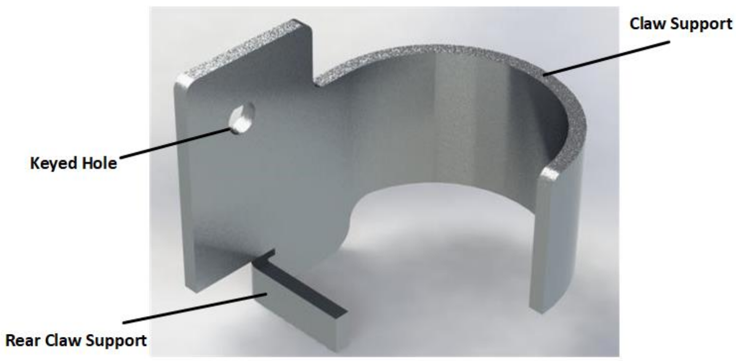

*Figure **Error! No text of specified style in document.**-15: Mounting Bracket Isometric View*

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~~3.1.2~~ 3.1.2 -Housing Assembly

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The housing assembly consists of three major components which interface with each other, in order to protect the internal components from outside elements, and hold the entire assembly together. These components are the Motor/Shaft housing, the End Cap and the Mounting End Cap. The Mounting End Cap interacts directly with the preexisting TM600 fork. The Motor/Shaft Housing is pressed into the Mounting End Cap and the End Cap as seen in Figure Error! **No text of specified style in document.**-16.

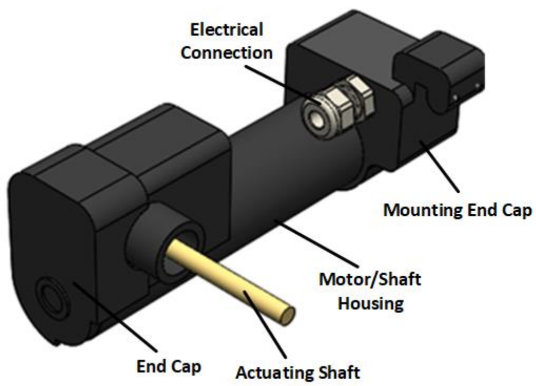

*Figure **Error! No text of specified style in document.**-16: Housing Assembly*

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~~3.1.2.1~~ 3.1.2.1 Mounting End Cap

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The Mounting End Cap (MEC) is a plastic cap with a cylindrical insert for a motor, one hole for electrical cabling and a mounting bracket for fastening to the TM600 fork. It effectively protects the Motor/Gear Train Assembly, guides the electrical connection from the motor to the pre-existing power supply, and secures the motor in place. The cap is made of machined Delrin, ensuring the greatest part lifetime, and weighs 57.5 g. It is press fit onto the circular section of the Motor/Shaft Housing keeping the Motor/Gear Train Assembly sealed from dust and water and has a hole in the rear of the circular section to enable fastening of the motor to the housing. The MEC has a mounting bracket on the side and is secured to the fork of the TM600 with two set screws. An electrical connector allows for easy attachment of the cap to pre-existing electrical cables. The features of this part can be seen in Figure 3.1.2.1 below.

The dimensions of the cap 51mm x 53.59mm x 68.5mm there is a 20mm typical radius fillet on all corners of the part to avoid stress concentrations. The motor is secured inside of the MEC by an M7-1.0 screw located in the centre of the press fit hole. The hole for electrical connection is threaded with ½-13 UNC so that a 0.5in waterproof nylon conduit can be passed to the Motor. The mounting bracket on the cap is 20mm wide, 24.8mm long, and 17.49mm high with the clearance for mounting is 5.33mm x 7.99mm as seen in Figure Error**! No text of specified style in document.**-17. There are two tapped holes for the #6-32 UNC set screws located 0.25in away from the bottom of the mounting bracket and are centred on the bracket 0.5in apart.

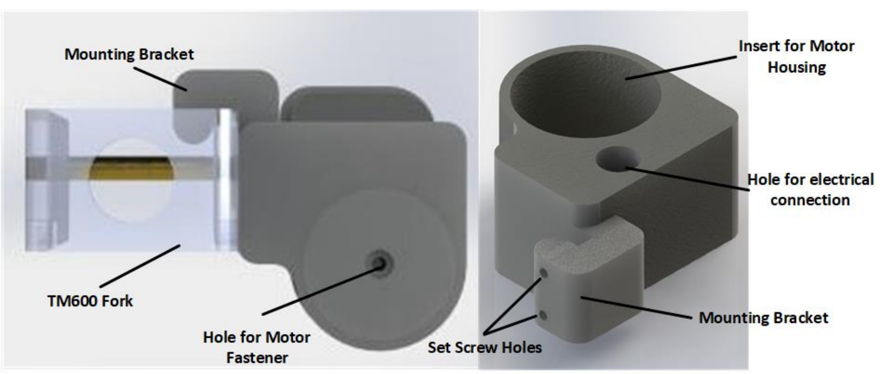

*Figure **Error! No text of specified style in document.**-17: Mounting End Cap*

The left image shows the rear view of the Mounting End Cap mounted to the TM600, the right image shows the isometric view.

~~3.1.2.2~~ 3.1.2.2 Motor/Shaft Housing

The Motor/Shaft Housing is a plastic, waterproof and dustproof case with a tube to house a motor and worm, the housing extends into a larger portion to house a spur gear, it has an additional hollow cylindrical extrusion extending from the side of the

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rectangular face perpendicular to the main tube to house a bearing and shaft. It is used to hold the gear assembly together and to provide structural support to the entire add-on. It is made of machined Delrin ensuring a strong lightweight part. It is press fit into both the mounting cap and the end cap preventing dust and water contaminating the gear train.

The housing has a wall thickness of 5mm, the tube has an inner diameter of 30.6mm, while the larger part is 60mm tall and 55mm wide. It has an overall length of 140mm and weighs 55g. A 5mm thick flange with four 4.47mm clearance holes is located 100mm from the circular end of the housing, enabling the motor to be mounted to the housing via four flat head screws, producing the greatest possible holding force while preventing the obstruction of moving parts. Two press-fit bearings are installed within the housing, one in a 0.5in diameter, 3mm deep indent, and the other within the 0.5in diameter, 5mm deep perpendicular cylinder the Actuating Shaft passes through. The overall shape and specific features can be seen in Figure Error**! No text of specified style in document.**-18.

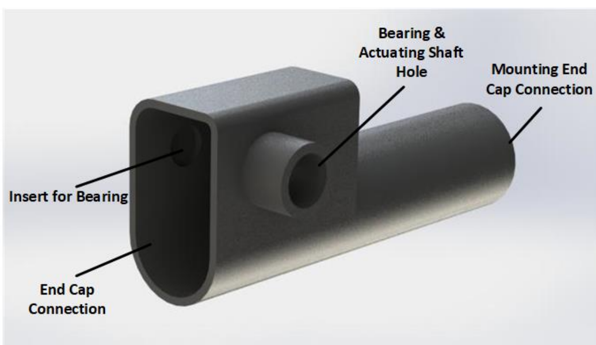

*Figure **Error! No text of specified style in document.**-18: Motor/Shaft Housing*

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~~3.1.2.3~~ 3.1.2.3 End Cap

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The End Cap is a five sided rectangular plastic box with two half circles cut from two of the walls and an internal cylindrical extrusion to provide dust and waterproofing to the internals of the Motor/Shaft Housing and ensure that the worm gear stays in place during rotation; it is press fit onto one end of the Motor/Shaft Housing.

The end cap is 18.5g and made of machined Delrin, and is 41mm wide x 65mm high x 23mm long with an edge thickness of 5mm as seen in Figure Error**! No text of specified style in document.**-19. Two half circles cut out from the wall on each high sides of the shaft that are 0.75in diameter in order to fit around the bearings in the motor housing. There is a circular 0.25in ID x 0.25in tall extrusion centred around the bottom radius of the part to seat the worm gear. A section of the wall cut out from the outside of the cap to prevent a clash with the claw assembly.

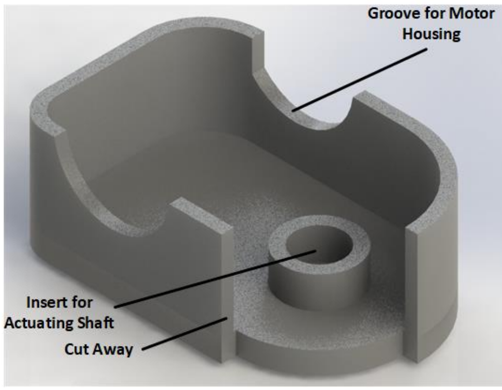

*Figure **Error! No text of specified style in document.**-19 : End Cap*

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~~3.2~~ 3.2 Conclusion

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The TM600 Add-On product is a user-friendly tool which is easy to install and dramatically increases the usability of the TM600 itself. Its modular construction promotes ease of transport, storage, installation and maintenance. Further, it is lightweight and inexpensive providing a valuable return on investment for the user.

~~3.2.1~~ 3.2.1 Cycle of Operation

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The cycle of operation of the TM600 Add-On product is two-stage. Firstly the claw begins at the lowered position and is actuated upwards 90deg. Then it is actuated from the raised position downwards back to the lowered position.

~~3.2.1.1~~ 3.2.1.1 Actuation of Claw Upwards

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When the claw is in the lowered position (opening facing the ground) a button is pressed, the motor is activated and rotates clockwise. The shaft protruding from the motor rotates the worm gear, which in turn, drives the spur gear. The shaft on which the spur gear is mounted rotates, actuating the rotation of the bracket and claw assembly upwards. When the claw reaches 90 degrees rotation, or the button is released, rotation stops. When the claw has reached 90 degrees from the starting position it is in the raised position.

~~3.2.1.2~~ 3.2.1.2 Actuation of Claw Downwards

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When the claw is in the raised position (opening perpendicular to the ground) two buttons are pressed the motor is activated and rotates counter-clockwise. The shaft protruding from the motor rotates the worm gear counter-clockwise which in turn, drives the spur gear. The rotation of the spur gear drives the Actuating Shaft, promoting the rotation of the bracket and claw assembly downwards. When the button is released or the claw has rotated 90 degrees rotation stops. When 90 degrees of rotation has occurred the claw has again reached the lowered position.

~~3.2.2~~ 3.2.2 User Value

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The TM600 Add-On Product is a versatile tool with the vital ability to move the TM600 Claw Assembly through a vertical rotational motion. It is fundamentally valuable to the bomb disposal technician who will be utilizing the tool; the modular construction allows the user to attach it to the TM600 without the need for tools or specialist skills. The minimal parts prevent confusion; simply the shaft attaches through the existing fork and claw assembly in place of the standard TM600 shaft, and the mounting bracket on the MEC is intuitive in its uncomplicated design. The lightweight design and attention to detail prevent the product from clashing with the claw, ensuring ease of use.

~~4.~~ 4 Calculations and Testing

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The validity of the design is based off of hand calculations performed on the shaft of the add-on, and calculations to ensure that the motor and gear system provide enough torque to actuate the claw loaded with a 15lb weight. FEA is performed on the major parts in the add-on that experience the torque which include the shaft, the housing, the coupling, the bracket and the end cap. Physical torque testing is done on the shaft, and the entire add-on is tested while attached to the TM600 to ensure that the product will perform as intended.

~~4.1~~ 4.1 Theoretical Testing

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FEA is performed on the shaft, the bracket, the housing, the coupling, and the end cap to ensure that there will not be failure during operation of the add-on. All FEA testing is done assuming a worst case scenario of 15 lb load 10 in away from the centre of the shaft. Hand and excel calculations are performed on the shaft and the gear system to ensure that the FEA results are valid and to completely ensure that the add-on will not fail under the worst case conditions.

~~4.1.1~~ 4.1.1 Hand Calculations

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Hand Calculations are performed on both the shaft and the gear set to ensure that the add-on performs similar to the FEA results that are taken from SolidWorks. In these calculations it is considered that the claw is under the worst case scenario where there is a 15lb mass projecting a 150 lb-in torque on the shaft of the add-on. It is considered that for this test there will be no press fit between the shaft and the claw so that the forces and the bearings are as far away as possible.

~~4.1.1.1~~ 4.1.1.1 Gear Calculations

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Calculations are performed on the gears to ensure that the selected gear ratios will allow for the motor to actuate the claw while carrying a 15lb load. For these calculations it is assumed that there are a range of motors and gears to select, and that it is both important to ensure that enough force is provided to the shaft while under the maximum torque of 150 lb-in. It is assumed for these calculations that a desired factor of safety of 1.5 is required.

~~4.1.1.1.1~~ *4.1.1.1.1 Gear Calculation Process*

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~~4.1.1.1.2~~ *4.1.1.1.2 Gear Calculation Results*

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~~4.1.1.2~~ 4.1.1.2 Fatigue Calculations

Calculations are performed on the output shaft of the add-on to ensure that the shaft will not fail due to fatigue within an unreasonable amount of time. Calculations are performed assuming that the input motor creates 8.32 lb-in of torque and that the gears are at a 1:30 ratio. It is important to aim for a factor of safety of roughly 1-1.5 for this situation as otherwise the shaft may fail early due to being subjected to repetitive motions.

~~4.1.1.2.1~~ *4.1.1.2.1 Fatigue Calculation Process*

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Insert equations and calcs

~~4.1.1.2.2~~ *4.1.1.2.2 Fatigue Calculation Results*

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Results table

~~4.1.2~~ 4.1.2 FEA Results

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Simulations were performed on the SolidWorks models in order to test for failure in the add-on. The highest possible forces were assumed which occur when the claw holds a 15lb package parallel to the ground. The package is then roughly 10 in away from the centre of the shaft creating the highest torque possible, of approximately 150lb.

~~4.1.2.1~~ 4.1.2.1 FEA on Shaft

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Simulations were performed on the shaft assuming that a 15lb load is being held horizontally by the claw creating a torque of 150lb-in on the shaft. In the worst case it can be assumed that there is no press fit acting between the claw and the shaft itself and therefore solely the bracket would be supporting the claw. This torque would then only be applied to the flat surface of the shaft and the gear supporting it an inch from the far side. This can be substituted in SolidWorks by using a remote restraint acting on the end of the shaft. A factor of safety of 1.3 was achieved on the shaft which means that it should not fail if this occurs.

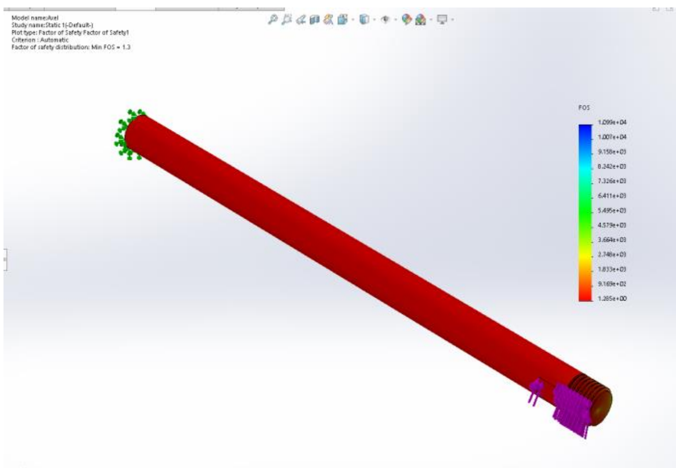

*Figure **Error! No text of specified style in document.**-20: FEA on Shaft*

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~~4.1.2.2~~ 4.1.2.2 FEA on Bracket

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Simulations were performed on the bracket assuming that the 150lb-in of torque would be acting inside the keyway due to the shaft supporting the load and that the bent end would need to stay in place from supporting the 15lb package. It was noted after the simulation was completed that the rounded end of the bracket was doing little to support the claw. This is due to the entirety of the weight being placed on the folded edge of the bracket meaning that there is no forces transmitted towards the other side. See Figure

3-16 below for image of FEA analysis. It was determined that there is still a factor of safety of 3.7 on the bracket meaning that it is safe from failure in this scenario.

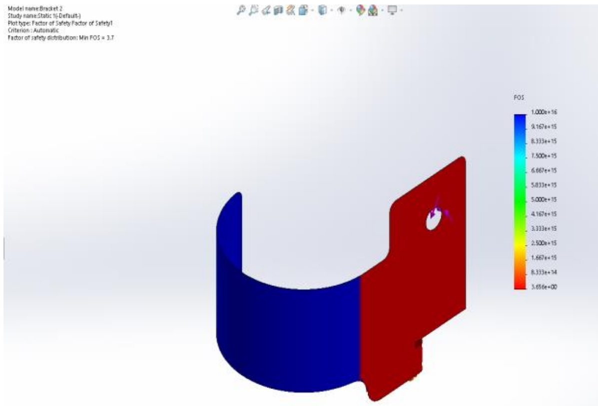

*Figure **Error! No text of specified style in document.**-21: FEA on Bracket*

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~~4.1.2.3~~ 4.1.2.3 FEA on Housing

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Simulations were performed on the housing assuming that there was a 150lb-in torque acting on the shaft, and a torque of 5lb-in acting on the motor flange, produced by the force of the motor itself, on the motor flange. it was assumed that the faces that come into contact with the fork of the TM600 as well as the end surface which is supported by the end cap are fixed from movement. A factor of safety of 3.3 was achieved on the housing which means that the housing is safe in this situation. See figure below for FEA analysis on the housing.

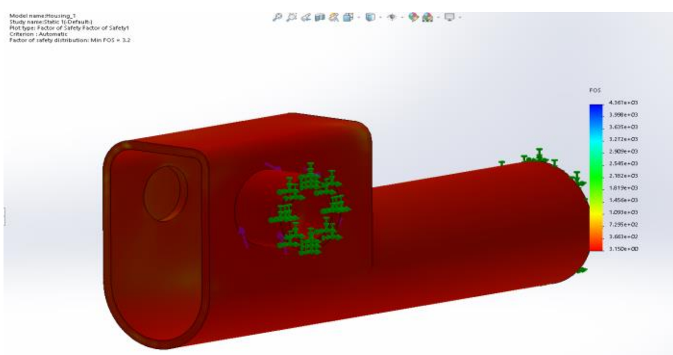

*Figure **Error! No text of specified style in document.**-22: FEA on Housing*

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~~4.1.2.4~~ 4.1.2.4 FEA on Motor Coupling

Simulations were run on the coupling assuming that there is a torque acting from the motor of 5lb-in, and a fixed end due to the worm gear resisting the movement of the system. See Figure 3-18 below for locations of both the torque and the fixture. It was observed that a factor of safety of 15 was achieved meaning the coupling is very safe from failure in the operation of the add-on.

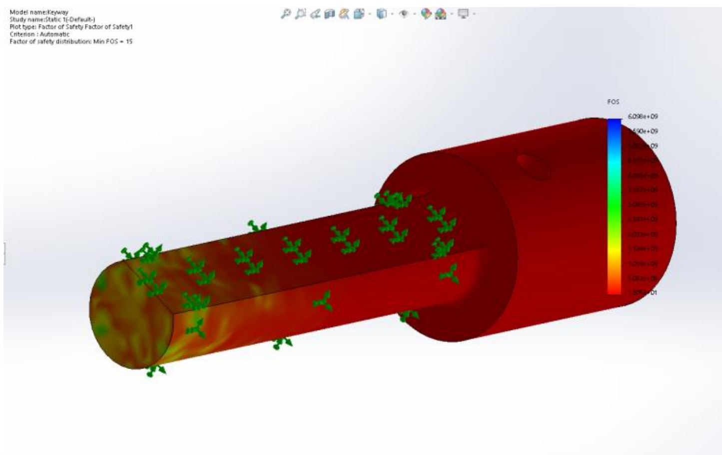

*Figure **Error! No text of specified style in document.**-23: FEA on Shaft Motor Coupling*

~~4.1.2.5~~ 4.1.2.5 FEA on MEC

Simulations were run on the end cap of the add-on assuming that it was supporting 150lb-in of torque coming from the shaft. This was applied to the inner surface of the housing where it fits on top of the housing. It was fixed along the side and around the hook where it comes into contact with the side of the fork assuming that there are two thumb screws holding it in place. Figure * below demonstrates how the end cap FEA was set up and where fixtures were applied. A factor of safety of 25 was achieved, indicating the component is safe in this situation.

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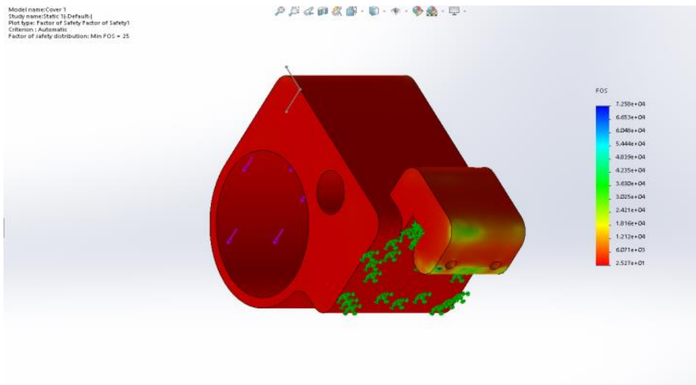

*Figure **Error! No text of specified style in document.**-24: FEA on MEC*

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~~4.1.2.6~~ 4.1.2.6 Results of FEA Testing

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Insert table of results here

~~4.2~~ 4.2 Physical Testing

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Physical testing will be performed on both the shaft and the entire add-on to ensure that the product will not fail during use and that it works as intended. Torsion testing will be done on the shaft to ensure that the metal does not reach the plastic stage of elongation ensuring that as little fatigue will be present as possible. Once the entire product is assembled there will be testing to ensure that the product rotates smoothly and without any shaking or bouncing and that the product will be able to lift a 15lb package with no issue.

~~4.2.1~~ 4.2.1 Shaft Torsion Testing

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Testing will be performed on a torque tester by incrementally adding a set amount of twist to the bar and measuring how much torque is being applied. The shaft is considered a success if there is no failure during the test and if the shaft remains elastic during the test and none of the twisting remains after the torque has been removed from the shaft.

~~4.2.1.1~~ 4.2.1.1 Objective

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To investigate and determine the modulus of rigidity, yield strength in shear and ultimate torsional strength of the actuating shaft

~~4.2.1.2~~ 4.2.1.2 Theory

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After the experiment, the value of angle of twist (ϕ) and the torque (T) will be obtained. By applying equation $t = (T \times r)/J$ to find shear stress, and $y = (r \times \phi)/L$ to find shear strain, then a shear strain vs shear stress can be. From the graph, the modulus of rigidity, the yield strength in shear, and the ultimate torsional strength for the material can be determined.

~~4.2.1.3~~ 4.2.1.3 Material & Equipment

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- Tecquipment Torsion Testing Machine
- Actuating shaft (Steel)
- Vernier Caliper

~~4.2.1.4~~ 4.2.1.4 Procedure

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Testing will be performed by a torque tester by incrementally adding the amount of torque being applied to the shaft and by measuring the angle of twist that is present after each iteration.

Step 1: Measure the length and the diameter of the actuating shaft with the Vernier Caliper.
Step 2: Draw a straight line on the actuating shaft with Sharpie marker
Step 3: Place the actuating shaft in the jaws of the Tecquipment torsion tester
Step 4: Adjusted the twist angle on the right-hand side and the spring scale on the top left-hand side so that the spring scale have a value of 0 (in.lb).
Step 5: After the spring scale is 0 torque. Record the twist angle
Step 6: Twisted the angle on the right-hand side for 2 degrees. Then adjust the load arm so the bubble spirit level in the tube is in the middle, which means the arm is perpendicular. After that recorded the torque
Step 7: Repeat the step 6 until the actuating shaft reach the elastic limit of the material which mean that until the torque is no longer increased linearly
Step 8: After reaching the elastic limit, twisted the actuating shaft to 10 degrees beyond the elastic limit. Adjusted the load arm, and record the torque
Step 9: Reduce the twist by 2 degrees until the torque back to 0, and record at each point.
Step 10: After the torque back to zero, crank up, twisted 6 degrees until failure occurs. Record torque at every new interval

~~4.2.1.5~~ 4.2.1.5 Data

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Table iii shows the dimensions of the specimen which is required in order to calculate the expected results of the physical testing.

Table iii: Specimen Dimensions

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Specimen	Dimension (in)
Length	
Diameter	
Radius	

Table iv highlights the results of both the physical testing and the calculated results.

Table iv: Results of Measured and Calculated Tests

Measured		Calculated		
Angle of Twist (degree)	**Torque (inlb)**	**Shear Strain, y**	**Shear Stress, t (psi)**	**Angle of twist (rad)**

~~4.2.1.6~~ 4.2.1.6 Calculations

- J = $\pi/2 \times r^4$
- Apply equation y = (r x ϕ)/L in order to calculate the shear strain. (Table 2)
- Apply the equation t = (T x r)/J in order to calculate the shear stress. (Table 2)

- Analysis:
  + Modulus of Rigidity, G: Calculate modulus of rigidity by finding the slope at elastic region: G =
  + The yield strength in shear (this point is where the actuating shaft reach the elastic limit of the material which mean that until the torque is no longer increased linearly):
  + The ultimate torsional strength (where the actuating shaft failed):

~~4.2.1.7~~ 4.2.1.7 Results

Table v: Summary Table of Results

Graph analysis	Value (psi)
Modulus of Rigidity, G	
Yield strength in shear	

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Ultimate torsional strength	

~~4.2.1.8~~ 4.2.1.8 Conclusion of Shaft Torsion Testing

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~~4.2.2~~ 4.2.2 Actuation Testing

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This Section describes the process of testing the TM600 Add-On Product when raising a 15lb package. The results of the testing are described within the section also.

~~4.2.2.1~~ 4.2.2.1 Objective

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To investigate if the add-on product of the TM-600 able to lift the 15lb package

~~4.2.2.2~~ 4.2.2.2 Material & Equipment

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- Add-on TM-600 product

~~4.2.2.3~~ 4.2.2.3 Procedure

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~~4.2.2.4~~ 4.2.2.4 Data

~~4.2.2.5~~ 4.2.2.5 Result & Discussion

~~4.2.2.6~~ 4.2.2.6 Conclusion

~~5.~~ 5 Modifications (if necessary)

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~~5.1~~1.1 **Modifications to Gear/Motor Train**

~~5.2~~1.2 Modifications on Housing Assembly

~~6.~~ 6 Analysis of Results and Discussion

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Overall discussion on all results of all types of testing
What worked
What did not work

~~7.~~ 7 Conclusion & Recommendations for Future Study

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Did it work, did it not, what else has to happen – better design/materials/thorough testing

~~8.~~ 8 References / Appendix

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