

# Additive Manufacturing Processes for Design, Maintenance and Sustainment – Phase I & II

## **Final Report**

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### **Acronyms and Abbreviations**

Term AM	<b>Definition</b> Additive Manufacturing	MMPDS	Metallic Materials Properties Development and Standardization
ARL	Army Research Laboratory	NASA	National Aeronautics Space Administration
CCDC	Combat Capabilities Development Command	NCMS	National Center for Manufacturing Sciences
CTMA	Commercial Technologies for Maintenance Activities	ODASD-M	R Office of the Deputy Assistant Secretary of Defense, Materiel
DOD	Department of Defense		Readiness
GE	General Electric	SLM	Selective Laser Melting
GVR-BOT	Ground Vehicle Robotics-Robot	SOPs	Standard Operating Parts
GVSC	Ground Vehicle System Center	TARDEC	Tank Automotive Research, Development and Engineering
IED	Improvised Explosive Device		Center Center
		TDP	Technical Data Package

#### 1. Executive Summary

The additive manufacturing (AM) process is the layering of a material such as plastic, resin, metal, or other elements, to create a fully functional product. Its popularity is growing exponentially as it is used in ever expanding and innovative ways, especially in the realms of maintenance and sustainment. With repair parts often difficult to acquire on an as-needed basis, AM offers a new and convenient way to keep equipment up and running. There is almost no industry that AM won't touch and influence.

A key benefit of AM is the potential to quickly create only the parts required at the point-ofneed thus reducing the need to create multiple, unnecessary parts and the associated delay in delivery of those parts where they are needed. As an example, The National Aeronautics Space Administration (NASA) pioneered the concept of AM for use on the space station as a method to create many different parts while in space from simple metal powder and a laser sintering AM process. This same process is what is now used routinely by General Electric (GE) and other aerospace manufacturers. In the future, it seems highly likely that multiple industries will adopt this approach as the machines and materials become more cost effective and better understood.

The Department of Defense (DOD) through the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) is aware of the benefits AM can bring to rapid design and deployment of new systems for our military personnel. For those tasked with maintenance and sustainment, this could be a game changing project. Targeting and replicating parts that can keep ground vehicles productive could add significant time to mission readiness and lower the costs of repair,

As a demonstration of what is possible, funding was provided through the Office of the Deputy Assistant Secretary of Defense, Materiel

Readiness (ODASD-MR) and the National Center for Manufacturing Sciences (NCMS) Commercial Technologies for Maintenance Activities (CTMA) Program to demonstrate how a small footprint AM system could be used to create parts at the point-of-need in a quick, accurate manner.

The following report discusses how AM can be used to enhance system readiness and sustainability. It documents how AM can be used for direct part replacement or system improvement. The project focused on the ability to use a single alloy to avoid cross contamination and single print system to achieve a small installed footprint. It demonstrated how currently available software and hardware can be deployed for part replacement or field upgrades. A currently fielded system, the iRobot 510 or Ground Vehicle Robotics-Robot (GVR-BOT), which is used for improvised explosive device (IED) disposal and reconnaissance, was chosen as a demonstration platform.

The project was broken into two phases:

- Phase I demonstrated how direct replacement parts can be created from scan data and material analysis of current parts (Appendix A).
- Phase II demonstrated how a system such as the GVR-BOT can be improved, and parts created for 82% of mechanical components that will match or increase the capabilities of the current GVR-BOT (Appendix B).

Only five surfaces required secondary machining. Again, this was done to demonstrate the versatility of AM and the ability to create parts that require a very small manufacturing footprint. In the future, distributed manufacturing will replace warehousing and inventorying of parts that may or may not be needed. When a part is needed, a digital data

packet would contain the information needed to create the part at the location and time needed.

#### 1.1 Results

The ability to "print" parts as-needed was demonstrated on a fielded system, the GVR-BOT. The lessons learned and design approaches used can be scaled and replicated to other fielded systems as larger AM systems become available. The project further demonstrated how a single alloy and single AM technology might be deployed to allow for a smaller footprint while serving a large variety of part needs.

#### Main Findings:

- Single alloy, single AM system replaced 82% of the mechanical components.
- Improvement opportunities afforded through AM which improve sustainability and readiness.
- Part for part replacement from scan data and simple metallurgical analysis.
- Small operational footprint with wide capabilities can be achieved with Selective Laser Melting (SLM) systems.
- Limitations to current processes and systems.

#### 1.2 Benefits

- Replacement parts can be created where and when needed from a qualified technical data package (TDP) and AM system.
- Reduced inventory of parts that may not be used.
- Reduced logistics of transporting the parts to where they are needed which results in savings in both time and money.

- Parts can be highly optimized to reduce build and operational costs through lightweighting and fuel efficiency gains.
- Features and design methods demonstrate how AM can improve serviceability and readiness. This has a huge potential to allow improvements captured through end user crowd sourcing if harvested properly.

#### 1.3 Recommendations

AM is currently in the early stages of production deployment and will continue to grow quickly over the next three to five years. The following recommendations are based on the results of this project:

- Create and validate TDPs for current systems based on part criticality and historical replacement usage.
- Limit part TDP to non-critical components and provide directives on parts that can be replaced and how.
- Validate parts and replacement of standard operating parts (SOPs) through facilities like Rock Island Armory's AM facility.
- Three technology areas that should be funded and heavily improved are:
  - 1. Distortion prediction software.
  - 2. Surface finishing that is capable of removing the surface fissures for enhanced fatigue resistance.
  - 3. Test and quantify material properties for AM parts and systems.
- Work on dual path component design specifications for future systems. An original equipment manufacturer (OEM) should provide designs and TDP for AM equivalent parts where possible.

#### 1.4 Invention Disclosure

Invention Disclosure Report(s): DD882 Sent to NCMS  $\square$ 

No Inventions (Negative Report) ⊠

#### 1.5 Project Partners

U.S, Army Combat Capabilities
 Development Command (CCDC)
 Ground Vehicle System Center (GVSC)

- U.S. Navy NAVAIR
- Army Research Laboratory (ARL)
- Pratt & Miller Engineering
- Kettering University
- National Center for Manufacturing Sciences (NCMS)

#### 2. Introduction

Readiness is the ability for a system to be operational when needed. AM can be a valuable component in the arsenal of fleet and system readiness. Imagine being able to print the part you need instead of "hoping" that it is in the warehouse or can be delivered in time (Figure 2-1).

Sustainability is the ability to keep a system operational during its entire life. Many of the systems used by our warfighters have extremely long-lifecycles and need to be maintained, even if some of the vendors no longer exist. In this case, AM can be used to create replacement parts on an as-needed and justified basis.

To demonstrate how AM is a key enabler to lightweighting the TARDEC GVR-BOT and how AM could be deployed in the field for onsite part manufacture, Pratt & Miller Engineering and TARDEC would partner to work under the NCMS CTMA Collaborative Agreement on a product enhancement of the TARDEC GVR-BOT using a small manufacturing footprint in the form of a single type AM process that allows parts to be made at the point-of-need. The existing GVR-BOT would be modeled, analyzed and fabricated to optimize strength and durability through the application of AM technology.

The objective was to demonstrate how AM can benefit DOD and leveraging the automotive industry in designing and building parts specifically for AM production. Emphasis would be on the tools and methods used for creating light, strong AM parts to further demonstrate the actual build of these parts and systems. This will enhance future design and build efforts by showing what can be done and potential pitfalls that should be avoided. These "lessons learned" are extremely important as building blocks for future projects. Additionally, by building a working example of an entire system, the project will build confidence in the design community that AM is not just a prototyping process but instead can be thought of when designing and fielding new vehicles.

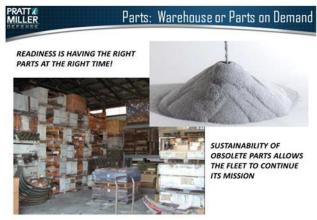


Figure 2-1. Parts on Demand vs. Warehousing of Parts

#### 3. Project Narrative

The following narrative documents the efforts of this project and how AM can be used for direct part replacement and how future designs can benefit from including AM as a fundamental part of the design process. As a secondary benefit, it further demonstrates how part optimization can be employed to reduce weight and build time.

#### 3.1 Phase I Overview

Phase I was a demonstration of direct part replacement. The GVR-BOT was chosen as the demonstration platform because of its relatively small size. GVR also possesses a small fleet of these robots available for testing and demonstrations. It demonstrated how parts can be directly printed and feature tolerances adjusted, allowing the parts to work in an as-printed condition with only hand tools needed to complete the parts for service.

#### **Small Operating Footprint**

In Phase I, the team explored the entire field of AM technologies, with the goal of discovering the most versatile and best fit for providing parts sustainment and readiness. In the team's estimation, Selective Laser Melting (SLM) was the best option to demonstrate AM (Figure 3-1).

#### **Single Alloy**

The team also decided to limit material choices to one metal alloy, as one alloy would allow the system to operate in the field with minimal downtime and reduced operator training. (Note: the systems ARE capable of printing many different alloys but require time and detailed cleaning if alloys are changed).

The Full System is shown in a 20x8 foot container (Figure 3-2).

#### 3.2 Phase II Overview

Phase II was a demonstration of how AM can be used to maintain, and even upgrade currently

fielded systems. The GVR-BOT was also utilized during Phase II but was reviewed with the GVR team to find improvements and remedies for problematic features.

#### **Sustainment of Current Assets**

Phase II of the project demonstrated how systems can be designed to take advantage of AM from their inception, which allows for early stage part release, followed by traditional manufacturing methods to keep costs down during the bulk of production (Figure 3-3). Once the initial procurement has been met, the Army can switch back to a fully qualified part with a complete AM TDP for sustainment of the system well into the future.



Figure 3-1. Example System Used to Create Parts

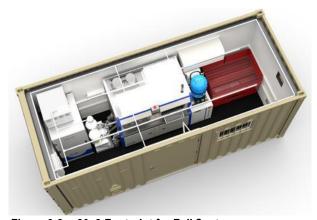


Figure 3-2. 20x8 Footprint for Full System



Figure 3-3. Direct Replacement of Parts from Scan Data and Material Analysis

#### Field Upgrades and New Designs

Another major advantage that an AM system could provide is allowing the warfighters to "print" parts that enable the upgrade or uparmoring of a system. Armor systems primarily employ highly hardened sheet materials, which cannot be bent or welded. The process of uparmoring a current system would be much easier if the depot had the ability to print armor joining features and mounting brackets, etc. (Figure 3-4) (Appendix B).

#### 3.3 Goal Setting

Phase I focused on how a system can use AM in a part for part replacement situation.

Phase II focused on how a currently fielded system can have full sub-assemblies replaced with similar or more capable assemblies. During this phase, the team explored the benefits and limitations in heavily using AM as a fundamental design constraint. To better understand the current system and any problems or improvement areas, the entire team met with the GVR team lead to brainstorm opportunities to improve the current BOT design.

The Phase II objectives were the following:

#### Primary Goal:

Create a new BOT that made from 80-85% printed components to match or increase the

capabilities of the current GVR-BOT. The new parts must be from a single alloy and single printing system in order to keep the fielded system footprint to a minimum.

#### Secondary Goals:

- Wider range of missions
- Faster teardown and repair
- Increased time between failures
- Minimize secondary operations on all AM parts
- Increase portability

## 3.4 Concept Creation and Down-Selection

#### How to achieve project goals:

- **Teardown and Reassembly Time** Far fewer screws and bigger seals.
- **Gearbox Failure** Addressed with better ring gear support, printed and cover for more robust seal surface to retain grease (Figure 3-5).
- **Longer Range** Wheeled version for better efficiency.
- Steeper Hill Climbing Segmented, printed track with better wheel to track engagement to eliminate skipping and the ability to print longer cleats for soft or mushy soil conditions.
- **Reverse Obstacle Climbing** With angled track and tensioner wheel (Figure 3-6).
- **Faster** Wheeled version will be faster and more energy efficient for certain missions (Figure 3-7).

Conceptual images of the various features were created and described, then the GVSC group was surveyed to determine the best goals or features to move forward. This step was critical in confirming the "voice of the customer" and what GVSC saw as valuable in the AM investigation.

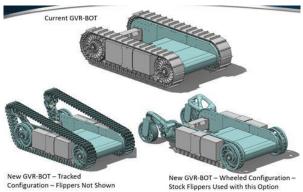


Figure 3-4. Example Options of Potential Field Upgrades



Figure 3-5. Original Motor and Gearbox with Grease Cover

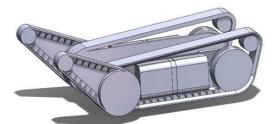


Figure 3-6. Concept Example of Improved Mobility
Field Upgrade

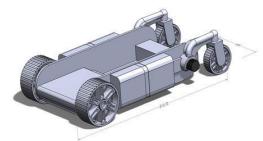


Figure 3-7. Concept Example of Improved Speed Option

#### • Modular and Configurable -

Multiple mission specific options can be employed with the only limitation being the warfighter's imagination. All subassemblies are interchangeable with current GVR-BOT systems (Appendix B).

- All Printed Parts Analyze and simulate load cases to create component load cases. Design and optimize each sub-system/part to handle the loads based on the material design allowables (Appendix C).
- Print Feature Samples Test
   Functionality of Various Feature
   Concepts This is very important
   since AM allows many features to be
   integrated into a single part
   (Appendix D).

#### 3.5 Tasks

## 3.5.1 Material and Process Characterization

Material characterization was investigated through several methods. The project employed material experts from Kettering University and consultations with both the material and AM system supplier, SLM and several consultations with NAVAIR and ARL. After investigating multiple sources, it was determined that fatigue data for aluminum alloys was not available, and the project was not budgeted for this level of effort. Currently, both NAVAIR and ARL are working on titanium and stainless alloy characterization. The primary load case driving the design for the GVR-BOT is a three-foot drop test. Given that fatigue was not considered a primary driver, tensile and compression tests were run to determine the design allowable as 80% of the lowest yield value found from testing. Test samples were printed in three different orientations. This testing showed the importance of understanding cooling stresses and support structures (Figures 3-8 and 3-9). For example, the first five samples of the horizontal bars cracked on the build plate before removal. After moving the part from 20mm above the plate to 50mm and adding supports under the center of the part, the next samples came out without issue but did have the lowest strength of the group (Appendix G).



Figure 3-8. Material and Process Test Coupons and Results

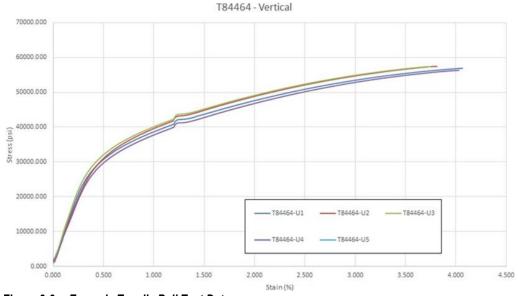


Figure 3-9. Example Tensile Pull Test Data

## 3.5.2 Concepting Future Systems and Field Upgrades

The team began the redesign for AM effort by first understanding any issues with the current GVR-BOT and what could be done to increase the BOT's mission capabilities.

The team met with the system managers to review known issues of which only the speed of assembly and gear failures were the only two items that were issues to be addressed. The next step was to brainstorm mission capabilities and potential improvements. For this effort, multiple sessions were held with operators and technicians to determine what might be desired in the field. Concept drawings were created of each option and ultimately voted on by a large community of users. The voting was used to down-select the best possible options. In this case, the team settled on two fundamental designs. The first was a tracked version with better traction for difficult environments and a wheeled version for improved

mobility and speed (Figures 3-10 and 3-11). All the parts created are fully interchangeable with the current systems. The reason for doing multiple systems was to demonstrate the ease of upgrades that AM brings since no tooling investment is required (Appendix B).

## 3.5.3 Use Environment and Load Case Determination

The project determined the BOTs were routinely subjected to drops and other high impact loads as the primary failure mode. As can be seen in the Figure 3-12, the arched plastic spoke in the wheel provided the major impact absorption (Appendix C).

While the drop test provided the primary load cases that drove sizing and design of the components, forging and assembly speed drove the sealing requirements and fastening feature design. Finally, rough terrain mobility drove the track and tensioner design while speed and agility drove the zero-turn wheeled design.

## 3.5.4 Feature Realization and Bench Tests

With the goals and overall architecture of the GVR-BOT decided, the team set about the task of determining the best way to achieve each goal. The team would meet to discuss and brainstorm many concepts for achieving the individual goals. Once the various individual goals had a variety of approaches to solve that goal, the team would rank the options and list the pros and cons for each option. In this way, each proposed feature solution could be graded as to the likelihood of it working as expected. The primary areas of concern were distortion or design robustness against tolerance deviation. This approach was replayed on each feature or feature set (Appendix D).

A good example was the tapered lock and O- ring sealing features that were tested (Figure 3- 13). The image shows one half of a test part that includes a dove tail O-ring groove

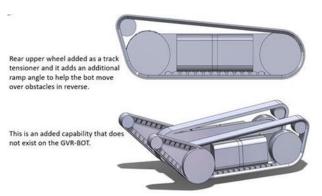


Figure 3-10. Tracked Version Field Upgrade

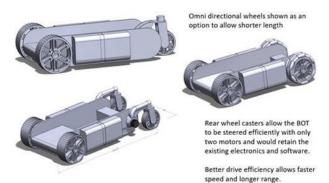


Figure 3-11. Wheeled Version Field Upgrade

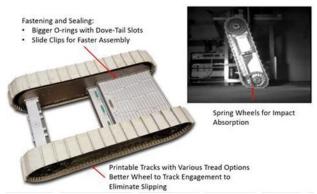


Figure 3-12. Drop Test and Upgrades



Figure 3-13. Tapered Tab and O-Ring Sealing Test
Part

and tapered tabs to create a locking and sealed attachment feature. The test parts successfully held 60PSI with only hand tightening. This gave the team confidence that an as-printed surface and tapered locking tabs were a viable design feature moving forward. This was ultimately used to fasten the side plates to the body in the final design.

Testing of fundamental features and printed part quality was repeated for any area of concern the team encountered.

When necessary, certain components were printed with a varying feature size to find the best nominal size for a certain feature. The track links are a good example of how the part dimensions were varied to determine the best dimension to use for a certain type of feature (Figure 3-14).

Another good example was determining the bore tolerances for the gearbox. The test article in Figure 3-15 was used to determine concentricity, parallelism and perpendicularity of printed bores.

From these print tests, the team determined the best feature or features that would be robust enough to meet the intended use case and be repeatable in multiple builds.

AM parts are basically cast parts or multi-pass, micro-welded parts. The distortion and surface finish are the largest areas for potential design variation. As such, the design must be capable of handling those variations or secondary operations will be needed, such as post print machining of certain features.

#### 3.5.5 Sub-Assembly Design and Test

The robot has various sub-systems that perform certain functions. The sub-systems are composed of many different features. While many AM influenced features such as fastening and sealing features, bearing bores and press fits

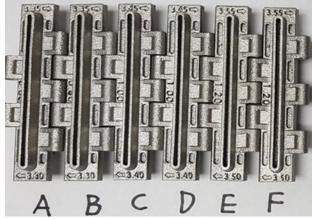


Figure 3-14. Tolerance Sweep on Track Link Design

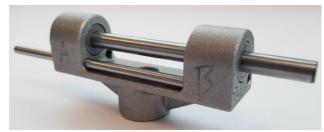


Figure 3-15. Bore Alignment and Perpendicularity

were tested at the base feature level, each subassembly was also printed and tested before creating multiple copies. One very beneficial aspect of AM is that very little setup time and cost is incurred which allows the design to be modified quickly and cheaply. As any design engineer can attest, 90% of any design is evolution and only 10% is revelation. AM allows the part design to easily evolve, as will be discussed throughout this report.

The major sub-assemblies in the AM-BOT are:

- 1. Wheels/tracks and tensioner
- 2. Flippers and related track tensioners
- 3. Main body, rear cross member and side plates
- 4. Spring joint attaching the flippers to the front axle
- 5. Motor and gearcase
- 6. Caster wheels and mounts

See Appendix E for component design and analysis.

Each sub-assembly was tested as it became available, and any improvements were made before the next article was printed. In all but one instance, the modifications took less than one day to update, reprint and test. The limited time required for modification highlights the evolutionary aspect of AM designs and how quickly a design can be tested and evolve into a better design.

#### 3.5.6 Full BOT Testing

Full system testing was accomplished at GVSC under the guidance of the GVR team. Testing included GVR's standard rework acceptance test as shown in Appendix C. The motor and gearbox sub-system was tested on a motor dyno at GVR.

Any issues found in testing were addressed and new parts printed. Again, this shows the ability for AM has in allowing a quick evolution of a design. As shown in Figures 3-16, 3-17 and 3-18 testing was done on each sub-system as it became available. Since the AM sub-systems were designed to be interchangeable with the current parts, each sub-system was tested as soon as it became available which greatly improved the time it took to evolve and mature a sub-system (Appendix F).



Figure 3-16. Forging Test and First Test of the Track and Tensioner System



Figure 3-17. High Speed Run While on the Flippers



Figure 3-18. Hand Stand and Rotation Tested per CCDC-GVSC Repair Protocol

#### 4. Conclusions

#### 4.1 Direct Part Replacement

In conclusion, the ability to print parts for direct replacement was demonstrated in Phase I with multiple parts on the GVR-BOT being printed and installed on an existing BOT. While this project focused on a fairly small vehicle, GE Additive has utilized and will be selling a system with a one cubic meter build envelope. Additionally, any of the materials that are printable with SLM are also weldable (Appendix A).

#### 4.2 Benefits of AM

In Phase II, the project demonstrated that many components can be printed and deployed in a single alloy, single print system and take advantage of lightweighting through optimization and quick part replacement through onsite AM and a digital TDP (Appendix B.

#### 4.2.1 Faster Design Cycles

The Phase II design and build showcases the art of the possible with AM for future projects which include:

- Quick design cycles driven by fundamental needs assessment (Figure 4-1).
- Improved functionality through early stage brainstorming sessions and test printing feature concepts (Figure 4-2).
- Increased design evolution since tooling investment is small or zero (Figure 4-3).

## 4.2.2 Reduce or Eliminate Secondary Operations

 Little or no secondary machining operations in most cases. The entire BOT assembly consisting of over 370 parts has only five machined surfaces.



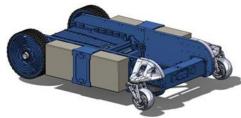
Figure 4-1. Concept Brainstorming

Several areas of the BOT will need to be sealed and a quick method of disassembly is desired. Two style of tapered lock style mounts were printed that incorporated O-rings to test the sealing capability.



Figure 4-2. Sealing and Tapered Post Feature Test Parts





Revised "Successful" Caster System

Figure 4-3. Fast Design Iterations and Evolution Caster Example

- Flipper assembly shows a highly complex system with rotating, spring loaded parts all done with AS PRINTED parts (Figure 4-4).
- Specific design features for quick assembly, O-ring sealing and bearing retention shown in Figure 4-5 and Appendix D were used.



Figure 4-4. Complex Assembly with Multiple Bearings and Springs Done Without Any Secondary Machining

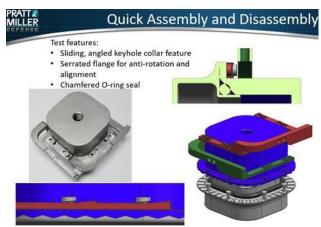


Figure 4-5. Bench Test Parts to Validate Fastening and Sealing

# 4.2.3 Reduced Weight and Material through Topology and Lattice Optimization

Demonstrated potential for weight savings through both topology and lattice optimizations. The latter can only be produced through AM.

A good example of how lattice structures can be used to support the thinner walls of a hollow section, the first pass caster arms are shown in Figure 4-6. In this case, the first design pass used a solid printed part while the second pass used a lattice structure to fill in the interior. Both part results are adequate to survive to loads but the lattice structure is significantly lighter (Figure 4-7) (Appendix C and Appendix E).

#### 4.2.4 Multiple Configurations

Demonstrated how AM allows multiple configurations to be easily deployed. This allows a system to be upgraded as new features or capabilities are required. Again, this is an artifact of no tooling investment. (Figure 4-8).

Figure 4-9 shows all three full systems of parts delivered as demonstration of AM readiness and



Figure 4-6. Caster Arm Design With and Without Lattice Optimization



Figure 4-7. Lattice Structure in Caster Arm



Figure 4-8. Tracked and Wheeled Version



Figure 4-9. Three Configurable GVR-BOTs Showcasing AM Potential

#### 4.3 Future Task Recommendations

- 1. Current Army systems are qualified at the vehicle level and specific component load cases and design criteria are not available. This issue prohibits the Army from producing parts that meet those criteria without involving the OEM. No process exists today that allows the Army to reverse engineer the component for actual field use. In the future, the PEO offices can request an equivalent AM part and TDP at the initial contracting phase. Additionally, guidance should be provided about how and when AM can be used to replace which parts.
- 2. Material properties need to be addressed and published, similar to DOT/FAA/AR-MMPDS-01 Metallic Materials Properties Development and Standardization (MMPDS). This will provide guidance on which material to

- use or if a component can be replaced by an AM equivalent. Investigate and document methods for improving surface finish and thus fatigue properties (Figure 4-10).
- 3. Better distortion prediction software. Small parts are not as much of a problem, but larger parts will need to be simulated to control distortion and determine the best orientation and build support strategy (Figure 4-11).

Thin sheet metal sections warped badly and required a corrugated surface to eliminate the bowing issue.

Ribbed housing caused even more distortion due to the heavier material on the large flat sections. Corrugating the surface allowed the part to have a constant wall thickness while also providing out of plane stiffness. The residual stresses were high enough to cause a crack or tear between layers as shown in Figure 4-12.

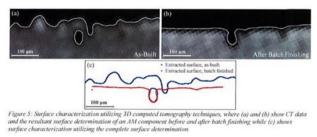


Figure 4-10. Surface Finishing Example from NAVAIR



Figure 4-11. Distorted Housing with No Ribs or Corrugation

The best result was achieved by creating a corrugated surface where the material thickness was constant, but the corrugation gave the surface some out of plane stiffness.



Figure 4-12. Distorted Housing with Ribs

#### 5. Benefit Impacts

The benefit to the Army is described in detail below and should allow the Army to maintain their readiness by printing required parts when and where needed. As most systems in our defense arsenal have a 40-year life requirement, the ability to produce replacement parts after a company may no longer exist is an absolute necessity.

In the commercial realm, aerospace companies have been printing production parts for over 10 years. The parts currently being produced are high cost, high value parts with features that can ONLY be created through AM. The design approach and technologies used in this project are directly applicable to many other commercial industries. The technology can produce high strength, lightweight parts through optimization and is highly customizable since the systems do not require tooling.

As the technology matures and costs come down, AM is being used in automotive and many other applications. For example, BMW recently released its first metal AM part on their i8 (Figures 5-1 and 5-2) and Ford has qualified several materials and process for use on production vehicles. The future of automotive part design will in many cases include a dual path design where an AM version will be printed for prototype and initial production runs. Once the parts are proven and volumes justify it, the part would be moved to traditional manufacturing approaches such as casting for the bulk of the production run, then once the vehicle is out of production, replacement parts would move back to being printed on demand; possibly at a regional facility or even at the dealership.

While this vision is 5-10 years away, this project has effectively demonstrated that the technology exists today and could be deployed in relatively short time. As new designs are created, AM will be considered in the overall lifecycle of the design. While this project

focused on metal AM, another currently produced product that uses AM is the Adidas shoe shown in Figure 5-3. The shoes were sold for \$250.00 and over 250,000 pairs were made. This again demonstrates that AM is becoming a cost-effective way to produce highly personalized and optimized commercial products.



Figure 5-1. BMW i8 First Serial Production Automotive

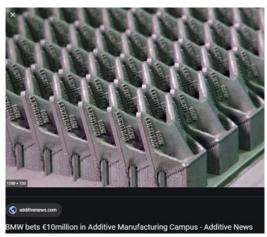


Figure 5-2. BMW Bracket as Produced on Build Plate



Figure 5-3. Adidas Tennis Shoe Printed Sole Example

#### **5.1 Project Specific Demonstrations**

The project demonstrated the following benefits.

## 5.1.1 Current Part Replacement Demonstrates Readiness

The parts shown in Figure 5-4 were printed, installed and tested based on laser part scans and material investigation. Material designation was determined through mass spectrometry and hardness testing (Appendix A).

#### 5.1.2 AM Centric Design Approach

- Ability to replace components with like components produced through AM with a single alloy and single AM system.
- Ability to improve a design through AM and quickly evolve a design.

#### **Feature Rich Design Options**

 Multiple feature examples are shown that take advantage of AM's unique capabilities.

A good example of a feature that allows faster repairs are the slide clips used to fasten the body to the side plates. In this example, 20 small screws were replaced by two slide clips on each side (Figures 5-5, 5-6 and 5-7). Removing and reinstalling the screws required 22 minutes as opposed to only three minutes when using the slide clips. The slide clips only became an option due to AM (Appendix D).

As another example of feature rich design options, the spring joint that connects the flipper arms to the BOT transmits torque along its rotation axis but needed to have a spring joint in rotation about the other two axes in the event of a drop. AM design allowed the part to have spline features that are barrel shaped (Figure 5-8). This allowed the spline to transmit torque but also allowed the coupled part to rotate about the other two axes. While creating an arched spline is possible with the right tooling, it can

simply be "printed" into the part when AM is used. In other words, the same machine that created the taper pins on the side plates is now creating arched splines on another part.



Figure 5-4. Current Parts vs. AM Equivalent



Figure 5-5. Original Part with Screws

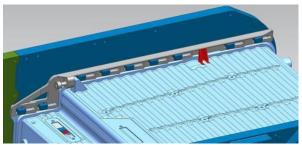


Figure 5-6. New Design with Tapered Pins and Slide Clips

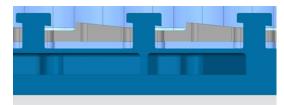


Figure 5-7. Closeup Showing Tapers on Slide Plate Posts and Slide Clips



Figure 5-8. Barrel Shaped Spline
Spring Joint Axle Coupling

#### Part Consolidation Available through AM

A good example of part consolidation was the main body (Figure 5-9). The original part consisted of two machined side flanges, a machined back section and a formed sheet metal part that was bonded and riveted together (Figure 5-10). In the AM design all four parts were combined into a single part that required no post machining other than drilling and tapping six holes. The new design even added a front handle mounting bosses that allow a front handle to be added (Figure 5-11). Something that was not possible in the original sheet metal design.

#### **Reduce or Eliminate Tooling**

Demonstrated multiple components that can be produced through AM and deployed in a single alloy and using a single printing system. In the case of the GVR-BOT, each BOT contains 370 printed parts. The majority are track links obviously. With a few test prints to qualify a feature, the part can be printed repeatably which proves the ability for AM to be digitized and printed in remote locations.

More details of each sub-assembly are shown in Appendix E.

As an example, the BOT with flippers has 244 track links that were assembled and installed as printed (Figure 5-12).

The project demonstrated what could be done in a small system footprint and with a single alloy. The system used to print all the parts is shown in Figure 5-13 in a 20x8 shipping container.



Figure 5-9. Original Main Housing vs. AM Main Housing

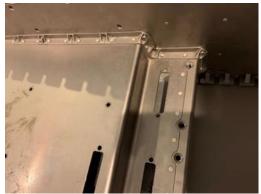


Figure 5-10. Original Main Housing Side Flange



Figure 5-11. New Design with Added Front Handle Bosses



Figure 5-12. Full Tracked AM BOT All Blue Parts
Printed

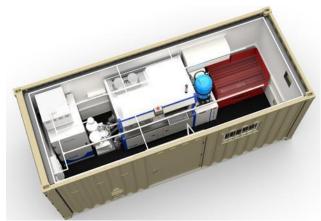


Figure 5-13. 20x8 Container and SLM 280 System with Cleanup and Ancillary Tools

## Weight and Material Savings through Topology and Lattice Optimization

AM parts are well suited for optimization and the project demonstrated this on multiple parts. In Figure 5-14 the track tensioner shows the "organic" nature of parts designed by topology optimization. This even allows for the hollow section where torsion or bending dominate the load and the material is driven to the outside of the design envelope. An example of this is the front, outer flipper arm as shown in Figure 5-15.

Another example of weight reduction and stiffness improvement is the area of lattice optimization. In this example, the interior of the part was filled with triangular beams that provide several benefits (Figure 5-16). Using optimized lattice structures internal to a part stiffens the part considerably and eliminates the need to remove any support structure required during the build (Figure 5-17). While not needed in this case, the lattice structure also can provide excellent heat transfer where the pins basically act as heat sink pins.



Figure 5-14. Optimized Track Tensioner





Figure 5-15. Optimized Hollow Flipper Arm



Figure 5-16. Caster Arm CAD with Lattice Filled Interior



Figure 5-17. Printed Caster Arm with Lattice Filled Interior

#### Appendix A – Part Replacement Investigation Results and Test Data



#### PROGRAM OVERVIEW

The program created additive manufactured parts to be used on the currently fielded GVR-BOT. The purpose of the program is to demonstrate part for part replacement capability found through Additive Manufacturing (AM).

Additionally, several fastener types were investigated that will allow "in the field" threaded features to be added to the parts without the need of additional milling equipment.

Finally, a proposed method of smoothing AM part surfaces for sealing purposes such as O-rings is reviewed.

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#### PROGRAM TASKS AND RESULTS

- Scanned components and compared to cad data
- Material comparison
- 3. Updated CAD data as required minimal hole location and size was modified originally
- 4. Additional design changes were made to the body due to part distortion from the printing process
- 5. Painted parts see notes on anodizing
- 6. Parts test fitted and robot run to demonstrate functionality
- 7. Fastener demonstration cut-away block
- 8. Fastener pull out strength comparison

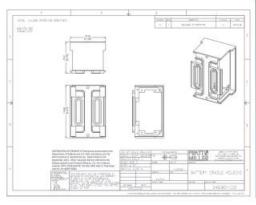
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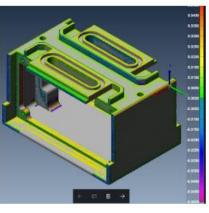


## Part Scan / CAD Review - Battery Cradle

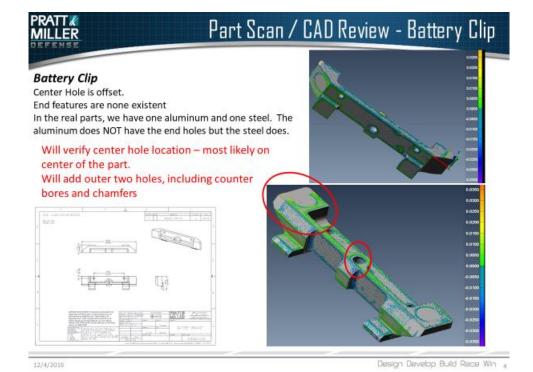
#### **Battery Cradle**

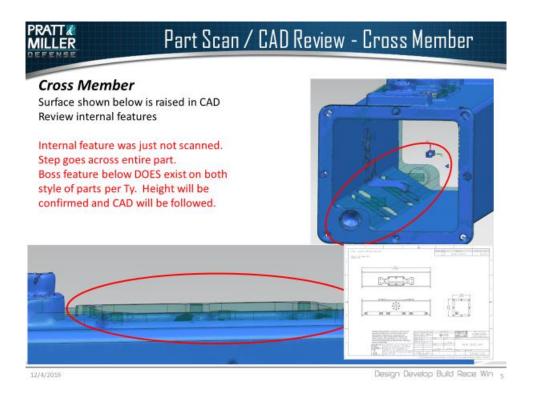
Holes and O-rings line up well Some areas the CAD model has more material. See image. Additional material in CAD model is to accommodate plastic AM parts currently being made. Aluminum parts will revert back to the smaller size so the weights are matched better.





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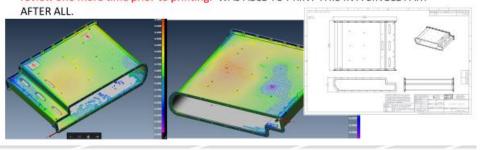




Looks good. Need to review a few main items as shown below:

- 1. Caliper and catalog review of connector spacing and hole size.
- 2. CMM hole pattern on side.
- 3. Where can or should we split the part? We may need to add some small ribbing or egg crate pattern to reduce warping. If so, were can we add this feature and were must we NOT add?
- 4. Can we get some assembled pictures or do we have a full assembly in CAD by chance?

Discussed potential split locations with Ty. It appears we have several options that should work. Will visit with suppliers to see which option seems best to them. Once a location and joint style have been discussed with the supplier, TARDEC and PME will review one more time prior to printing. WAS ABLE TO PRINT THIS IN A SINGLE PART



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#### **Material Comparison**

All current parts were confirmed to be 6061-T6 and 0 aluminum in wrought and sheet form. Three of the four components were made from CNC machined billet aluminum while the main body part was made from three CNC machined billet parts and a formed sheet metal part. All held together with solid rivets.

While not a direct replacement for 6061-T6, AlSi10Mg from EOS was used and should provide very similar performance.

Part Number	Part Name	Grams	LBs	Hardness (HRA)
D421801-1000A	Battery Bracket - ALUMINUM	25	0.06	TBD
D421801-10005	Battery Bracket - STEEL	75	0.18	75
D421801-1100	Battery Cradle Housing	260	0.58	37
D421801-1200	GVR-Bot Housing	770	1.7	40
D421801-1300	Rear Cross Bar	250	0.56	40

	Yield	Ultimate	Elongation	Data Source
6061-T6	276	310	17	MatWeb
6061-0	55.2	124	25	MatWeb
AlSI10Mg - no heat treat				EOS
in plane	270	460	9	
in z direction	240	460	6	
AlSI10Mg - yes heat treat				EOS
in plane	230	345	12	
in z direction	230	350	11	

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#### **BODY MODIFICATIONS DUE TO DISTORTION**

The type of Additive Manufacturing being used is Selective Laser Melting (SLM) which obviously introduces heat and cooling distortion that can be difficult predict. Large, thin, flat surfaces such as those found on the main body are most likely to warp and this happened on the first build of the part. Three attempts were taken before a suitable part was produced:

- 1. The first attempt was with no changes to the part. Unfortunately, the large flat areas bowed outward and were not acceptable.
- A second attempt was made were a 2mm high rib pattern was added to the bowed surfaces but this approach faired even worse as pictures show.
- 3. The third attempt stiffened the out-of-plane surface coregations that resembled sheet metal stamped ribs. This approach worked well and should be considered whenever a large, flat area must be made.

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#### First Body Print

#### Body Printed Identically to the First Part



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#### Painting vs. Anodizing

The parts were painted blue to make them visually different from the non-printed parts. The parts were painted instead of anodized due to the lack of an anodizing vendor that is capable of passivating the parts correctly. The high silicon content in the allow prohibits the growth of the aluminum oxide tubes that capture the die and thus are not easily anodized.

There appear to vendors in Europe capable of handling AM materials, the program was unable to identify any U.S. based companies currently working in this area. Further investigation continues and will be discussed in phase II of the GVR-BOT project. A sample part was tested but resulted in only blackening the part. The black would also rub off over time.



Sample Part Anodized Using Standard Aluminum Process

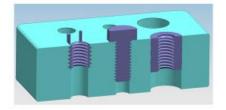
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#### **FASTENER FEATURE STYLE**

- · Three examples are shown below. Others could be used.
- · The block has two rows of three holes.
- One side would be pulled out and the pull out force recorded.
- The other side would only have the fasteners and inserts installed.
- Both sides would be sectioned so we can see how the fastener looks installed and how the failure mode looks.
- The block is 3" x 2" x 1" with 5/16-18 bolt





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### **Original and Printed Part Comparison**



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## Appendix B - Phase II Design Goals and Concept Analysis



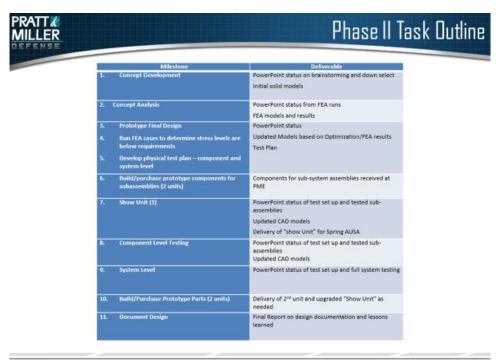
CREATE A NEW BOT THAT WILL BE MADE FROM 80-85 PERCENT PRINTED COMPONENTS AND WILL MATCH OR INCREASE THE CAPABILITIES OF THE CURRENT GVR-BOT

### Goals to achieve with new BOT

- wider range of missions
- faster teardown and repair
- 80-85% of the mechanical parts are printed from only one machine and material
- · increased time between failures
- minimize secondary operations on all am parts
- · increase portability

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- ➤ IMPROVE DISASSEMBLY SPEED BY REDUCING FASTENER COUNT
- IMPROVE RELIABILITY WITH MORE ROBUST GEARBOX AND NON-SLIP TRACKS



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### How to accomplish our GOALS:

- · Teardown and Reassembly Time Far fewer screws and bigger seals.
- Gearbox failure Addressed with better ring gear support, printed and cover for more robust seal surface to retain grease.
- Longer Range Wheeled version for better efficiency.
- Steeper Hill Climbing Segmented, printed track with better wheel to track
  engagement to eliminate skipping and the ability to print longer cleats for soft or
  mushy soil conditions.
- Reverse Obstacle Climbing with angled track and tensioner wheel.
- Faster Wheeled version will be faster and more energy efficient for certain missions.
- Modular and Configurable Multiple mission specific options can be employed with the only limitation being the warfighter's imagination.
- All Printed Parts

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## Material Properties

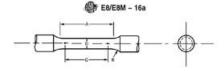
**Material Properties** 

Tensile Test ASTM E8/E8M Compression Test ASTM E9

5 tests each from three different orientations Total of 15 tensile tests and 15 compression tests. This will set the design allowable stress targets for the parts.







Dimensions, min (in.) For Test Specimens with Gauge Length Four times the Diameter (E8)											
	Standard Specimen	Small-Size Specimens Proportional to Standard									
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5						
G-Gauge length	50.0 ± 0.1	36.0 ± 0.1	24.0 ± 0.1	16.0 ± 0.1	10.0 ±0.1						
	12.000 ± 0.0051	(1.400 ± 0.005)	(1.000 ± 0.005)	(0.640 ± 0.005)	10.450 ± 0.0051						
D-Diameter (Note 1)	125 ± 0.2	9.0 ±0.1	6.0 ± 0.1	4.0 ± 0.1	2.5 ± 0.1						
	(0.800 ± 0.010)	(0.350 ± 0.007)	[0.850 ± 0.006]	(0.190 ± 0.003)	(0.113 ± 0.002)						
#i—Radius of fillet, min  A—Length of reduced parallel section, min  (Note 2)	10 [0.375]	8 [0.25]	6 [0.186]	4 [0.156]	2 (0.094)						
	56 [2.25]	45 [1.75]	30 [1.25]	20 [0.75]	16 (0.625)						

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## PRATT & MILLER

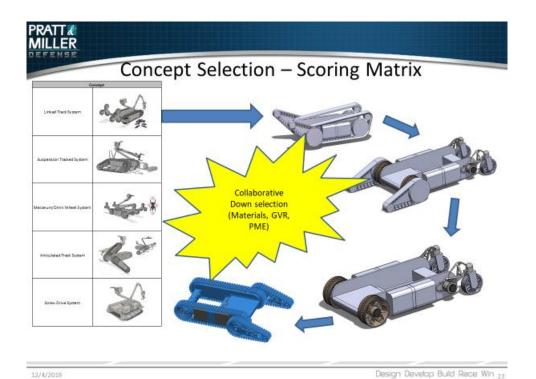
## Material Testing

### 15 tensile samples printed and 15 compression samples



	TENSILE TEST E8				COMPRESSION TEST E9				
	2% Yield Stress KSI	2% Yield Stress Mps	Ultimate Stress PSI	Stress MPa	Dia (m)	Area (in2)	2% Yield Load Lbs	2% Yield Stress KSI	2% Yield Stress Mpa
HORIZONTAL BUILD	25,7	177	43.5	300	0.513	0.207	7,401	35.7	246
	21.1	145	36.4	251	0.512	0.206	7,229	35.1	242
	22.3	154	38.6	266	0.514	0.208	7,241	34.9	241
	23.0	159	35.9	248	0.513	0.207	7,254	35.1	242
	22.1	152	37.5	259	0.515	0.208	7,255	34.8	240
AVERAGE	22.8	157.5	38.4	264.6	0.513	0.207	7,276	35.1	242
45 DEGREE BUILD	32.5	224	56.8	392	0.509	0.203	8,322	40.9	282
	34.1	235	57.4	396	0.509	0.203	8,134	40.0	276
	34.0	234	57.3	395	0.508	0.202	8,116	40.1	276
	32.8	226	56.3	388	0.507	0.202	8,027	39.7	276
	32.9	227	56.9	392	0.506	0.203	8,179	40.3	278
AVERAGE	88.8	229.3	56.9	392.6	0.508	0.203	8,156	40.2	277
VERTICAL BUILD	33.8	233	56.9	392	0.510	0.204	7,841	38.4	265
	33.4	230	56.5	390	0.510	0.204	7,622	37.4	258
	32.9	227	55.0	379	0.510	0.204	7,827	38.3	264
	32.1	221	56.6	390	0.509	0.204	7,544	17.0	255
	33.4	230	55.1	350	0.508	0.201	7,815	38.5	265
AVERAGE	33.1	228.4	56.0	386.3	0.509	0.204	7,730	37.9	261

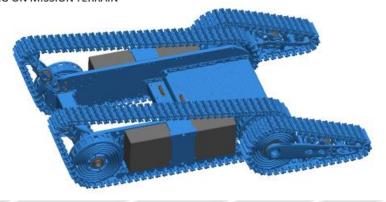
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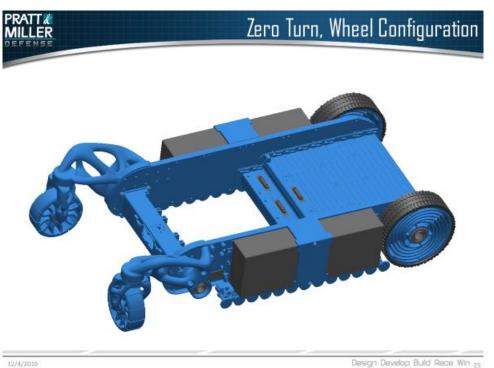
Fully Configured Tensioned Track

THE GOAL WAS 80-85% PRINTED METAL PARTS - BLUE PARTS ARE PRINTED PARTS

MISSION CONFIGURABLE – MULTIPLE CONFIGURATIONS CAN BE CREATED AS WELL AS DIFFERENT TRACK DESIGNS DEPENDING ON MISSION TERRAIN



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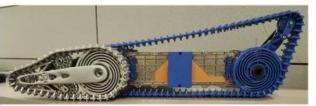


### **Flipper**

- Fully assembled and ready to test.
- Plastic flipper uses original detent balls and plunger
- Aluminum flipper uses all new, and printed detents and plunger









### First outdoor test of the track, wheels and tensioner.



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## Appendix C - Load Definition and Simulation



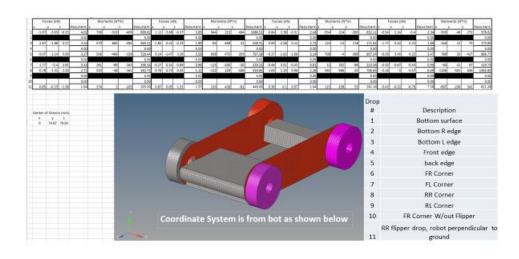
"The test item (the robot and the OCU each) will be subjected to Handling Drop Shock IAW MIL-STD-810F Method 515.5, paragraph 4.5.5.1 and Table 516.5-VI.

The RCV (Ty: Remotely Controlled Vehicle, the robot) will be assembled into its normal operational configuration. The height of the drops to be performed will be determined based on weight and largest dimension of test item. (Presumably, the robot in operational configuration weighs less than one hundred pounds and will therefore be subjected to drops of heights forty-eight inches or thirty inches, depending on largest dimension of test item.) The robot will be dropped in nine orientations: bottom surface, and each corner and edge of the bottom surface. The impact point or surface for each drop will be documented. After each drop, the test items will be visually inspected for any damage and an Operational Check performed. The condition of the item will be documented and photographed. Any safety related condition will be documented with a TIR (Test Incident Report). Any anomaly will be reported immediately to the Test Manager and the RS JPO POC prior to proceeding with additional drops."

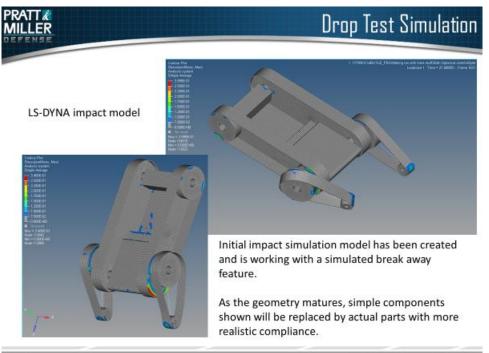
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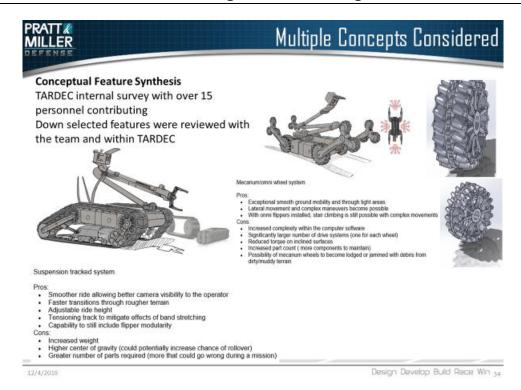


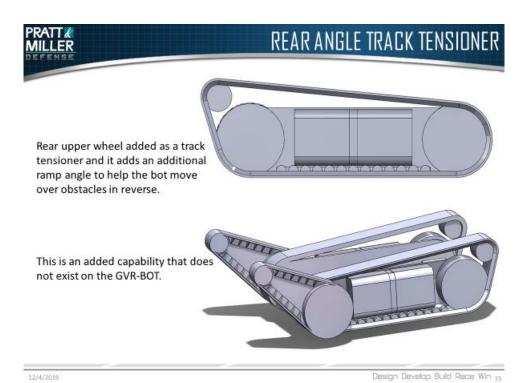


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## Appendix D - Feature Set Design and Testing

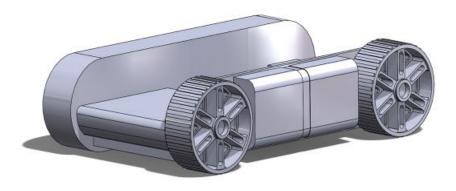






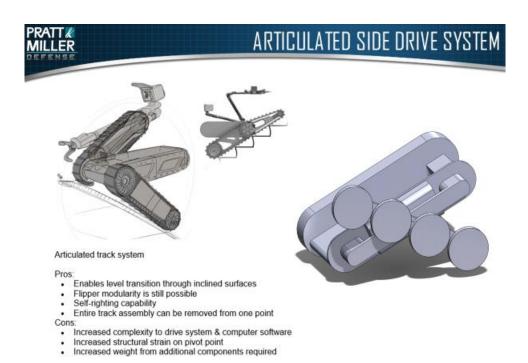
Wheeled option is well known and would add range and speed to the GVR-BOT.

Current electronics do not include a steering control system so this approach would have to rely on skid steer or have additional electronics and software upgrades.

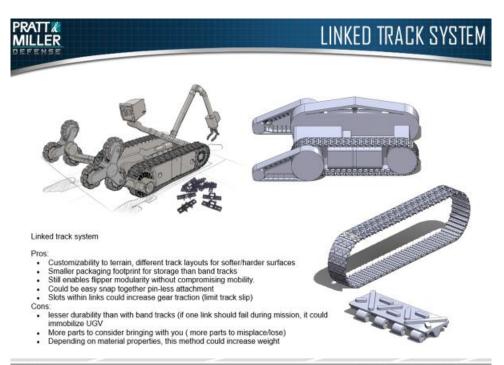


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### Suspension tracked system

### Pros:

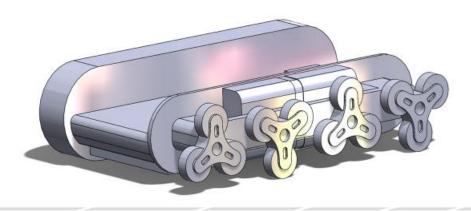
- Smoother ride allowing better camera visibility to the operator Faster transitions through rougher terrain
- Adjustable ride height
- Tensioning track to mitigate effects of band stretching
- Capability to still include flipper modularity

### Cons

- Increased weight
- Higher center of gravity (could potentially increase chance of rollover)
  Greater number of parts required (more that could go wrong during a mission)



Gives ability to traverse rough terrain. Down side is rough operation on smooth surfaces. Approximate sinusoidal motion that would be difficult to smooth out.



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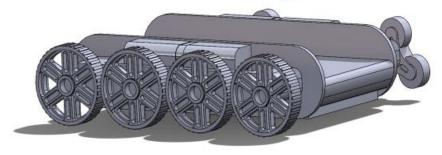
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Eight wheel system would require skid steer. Similar to system shown in the last page except this one uses round wheels for smooth motion. If wheels were replaced with "track wheels", bottom contact surface could be almost fully covered.



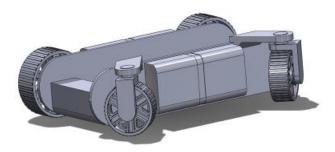
The Reconfigurable Wheel Track in Track mode.



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This system uses four independent wheel motors and four steering motors. All four corners are independent and have 180 degrees of motion. This allows the platform to turn about it's center as well as move in any direction. Would require additional electronics and software upgrades.



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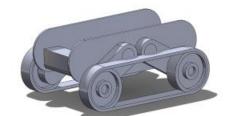
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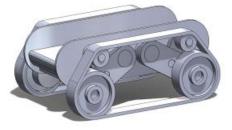


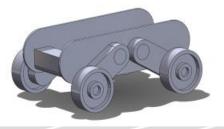
## SWING ARM SUSPENSION

Swing arm suspension could be tracked or untracked and would allow compliance under the track, between the wheels for additional traction.

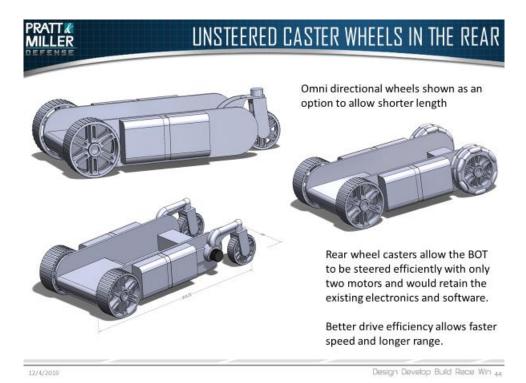
Wheeled version would be skid steer but would be more compliant.



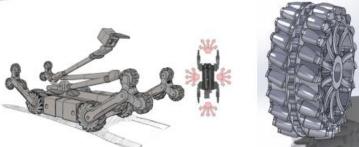




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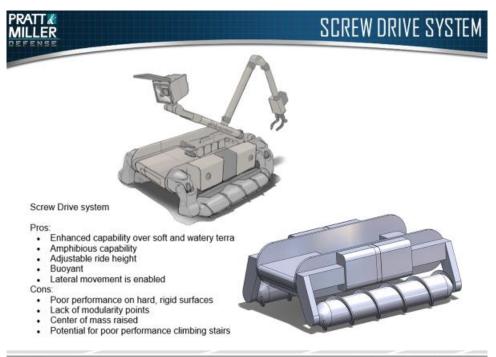
MECANUM/OMNI WHEEL SYSTEM



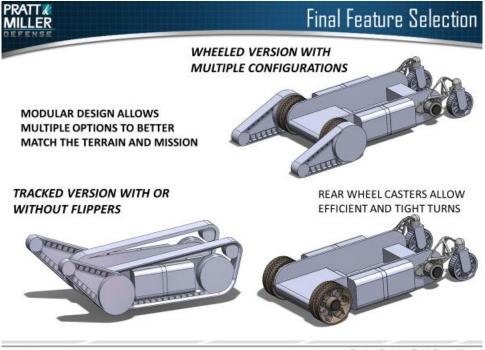
Mecanum/omni wheel system

- Exceptional smooth ground mobility and through tight areas
  Lateral movement and complex maneuvers become possible
  With onmi flippers installed, stair climbing is still possible with complex movements
- Increased complexity within the computer software
- Significantly larger number of drive systems (one for each wheel)
- Reduced torque on inclined surfaces
- Increased part count ( more components to maintain)
- Possibility of mecanum wheels to become lodged or jammed with debris from dirty/muddy terrain





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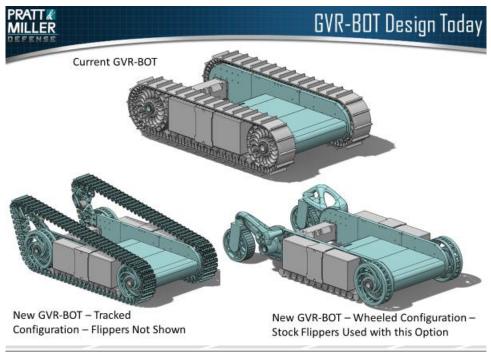
## FEATURE DESIGN, BUILD AND VALIDATION

### **Common Features Found on the Robot**

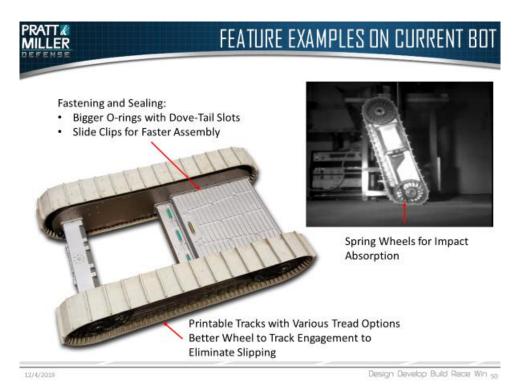
- 1. Shock Absorption
- 2. Joining
- 3. Sealing
- 4. Quick Assembly and Disassembly
- 5. Bore Tolerances and Alignment
- 6. Large, Thin Features Sheet Metal Replication

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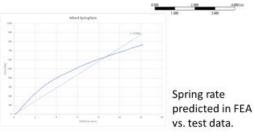
## **Shock Absorption**

### **BASELINE DELRIN WHEEL**

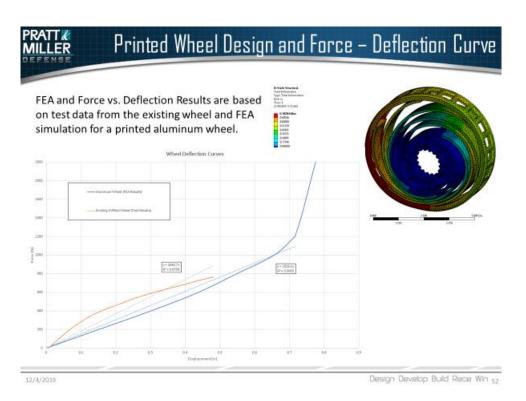
The Delrin wheel is currently used as the primary shock absorption feature. While difficult to match the ductility found in Delrin, the team did find a geometry that matched the force deflection curve of the Delrin wheel while being printed in Aluminum.







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# Printed Mold Example - Plastic Component Creation

### Optional Manufacturing Method for Creating Plastic Parts

The example shown to right could be used to create the wheel by first printing a mold. Then fill the mold with urethane material. Once the urethane has cured, the new part can be removed from the mold and put into service.





Example tool showing how AM could be used to print a tool and then cast urethane parts could be made. This opens up a wider range of material options.



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Several areas of the BOT will need to be sealed and a quick method of disassembly is desired. Two style of tapered lock style mounts were printed that incorporated O-rings to test the sealing capability.

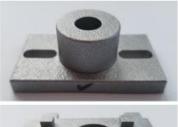
### Second Style - Slide Lock

Did Not Work – Clearances were too tight and the base bowed upward. The part would NOT slide together











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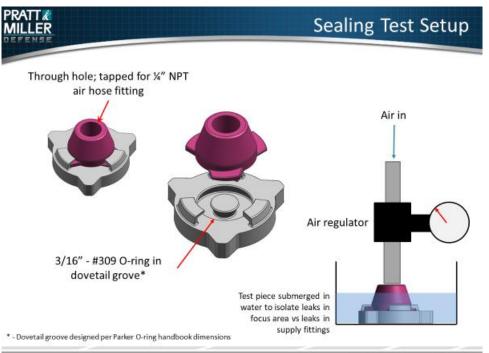


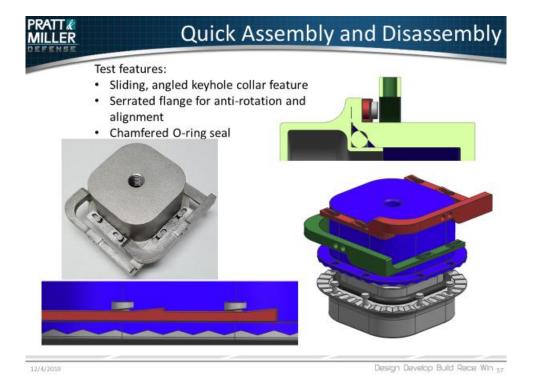
## Polished Sample - Single Media Vibratory Tumbler

This is a pretty aggressive material removal example and can be lessened to reduce less metal.

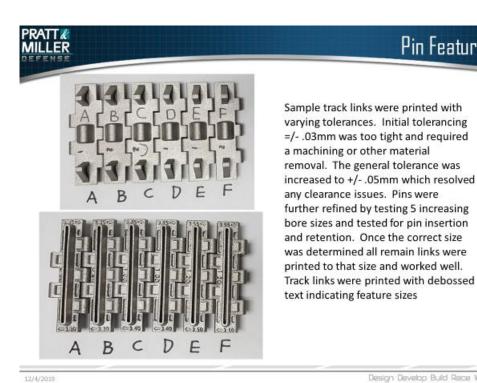


12/4/2019

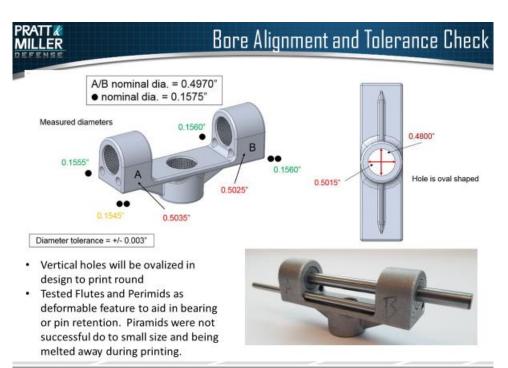




Pin Features



Design Develop Build Race Win sa





RATT & BODY MODIFICATIONS DUE TO DISTORTION

The type of Additive Manufacturing being used is Selective Laser Melting (SLM) which obviously introduces heat and cooling distortion that can be difficult predict. Large, thin, flat surfaces such as those found on the main body are most likely to warp and this happened on the first build of the part. Three attempts were taken before a suitable part was produced:

- The first attempt was with no changes to the part. Unfortunately, the large flat areas bowed outward and were not acceptable.
- A second attempt was made were a 2mm high rib pattern was added to the bowed surfaces but this approach faired even worse as pictures show.
- The third attempt stiffened the out-of-plane surface coregations that resembled sheet metal stamped ribs. This approach worked well and should be considered whenever a large, flat area must be made.



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#### Gearbox Problem:

The current gear set between the motor and drive axle uses a 90° bevel gear set that can separate between the gears under heavy load. This creates metal shavings from the gear teeth and the grease heats up, then drips onto the electronics boards causing further damage.

#### Remedies considered:

- 1. Create a more robust bearing and housing arrangement for the current bevel gears.
- 2. Convert to spur gears with double supported shafts and fully sealed housing.
- Integrate an off the shelf planetary gear set and re-package the electronics to accept the new configuration

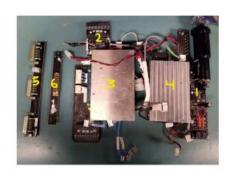


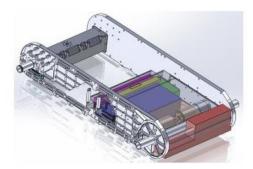
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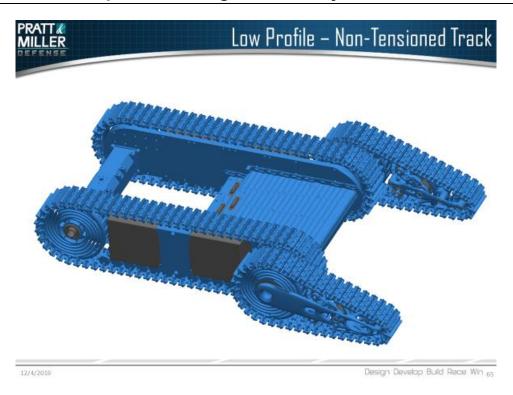


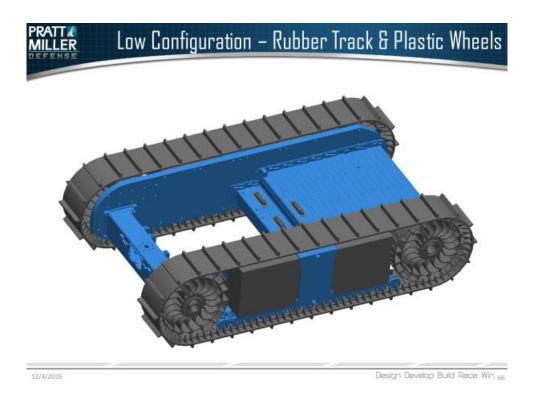
### Electronics CAD acquired - no scanning required



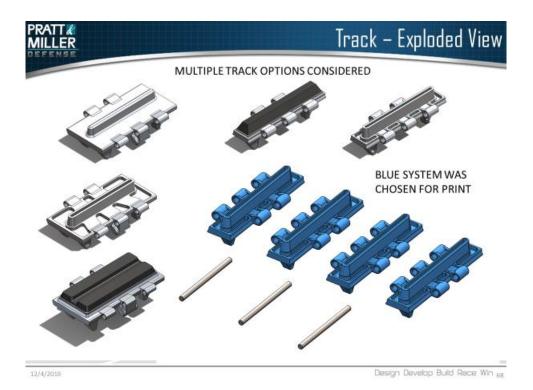


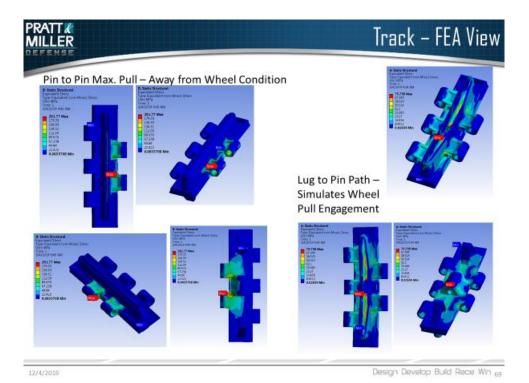
## **Appendix E – Component Design and Analysis**

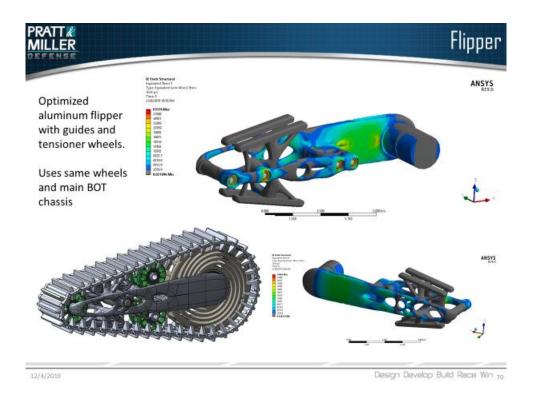












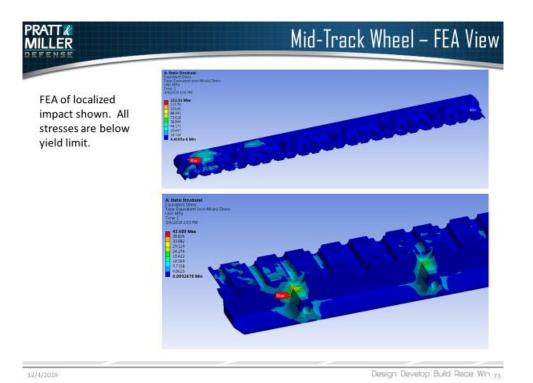




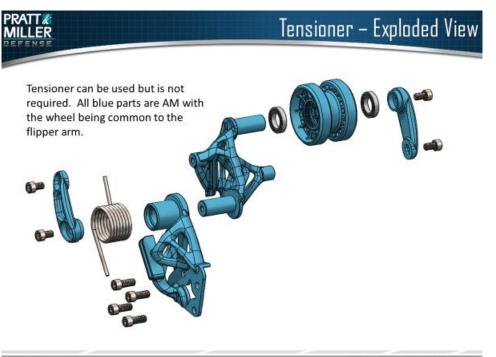
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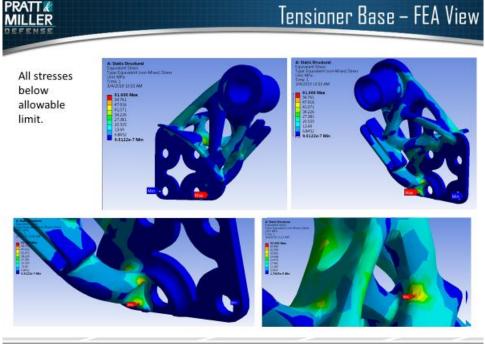
12/4/2019



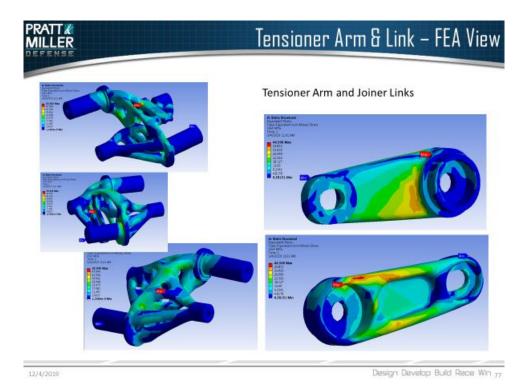
Tensioner will fit both the new BOT and the GVR-BOT



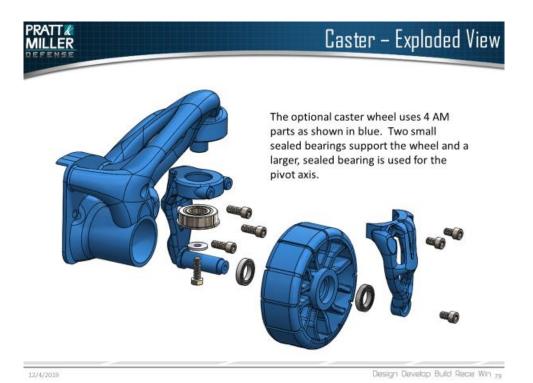
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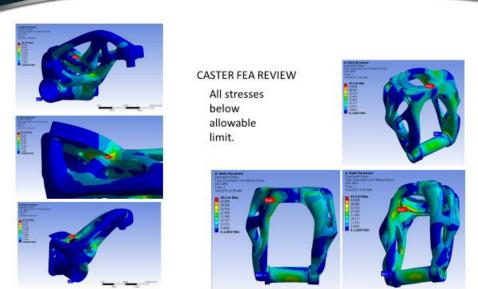
17/4/7010







PRATT & Caster - FEA View



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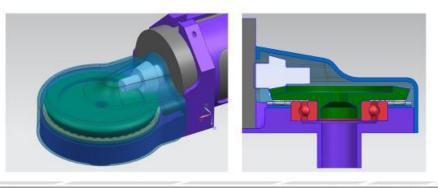


After reviewing the planetary motor and driver board packaging more, we could NOT find a packaging arrangement that allowed the configuration to be used.

### Instead we added the following features:

Gear separation: Fixed by using a backside thrust bearing on the main gear.

Grease Leakage: Fixed with a fully sealed cover.

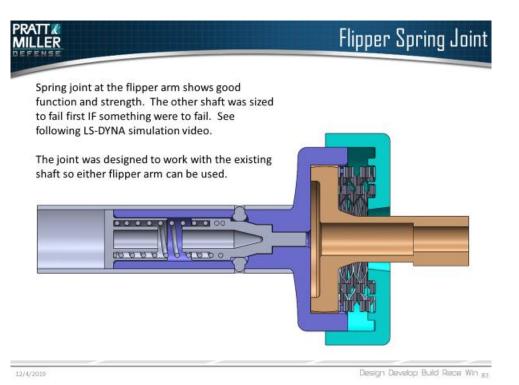


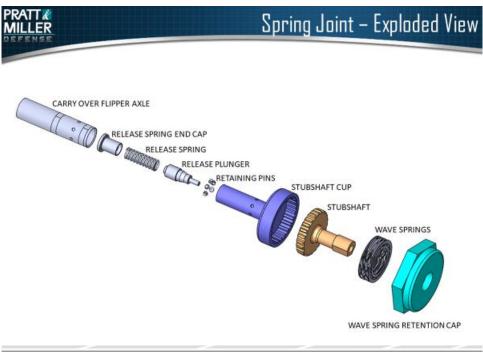
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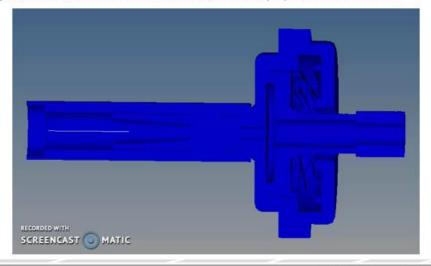
12/4/2019





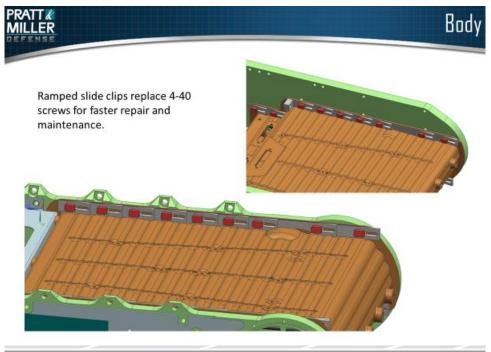
## Spring Joint – Simulation to Break – LS-DYNA

Spring joint was added to the flipper arm to soften the impact in a drop condition. The joint was further refined to allow the outer, more easily replaced shaft to fail first.

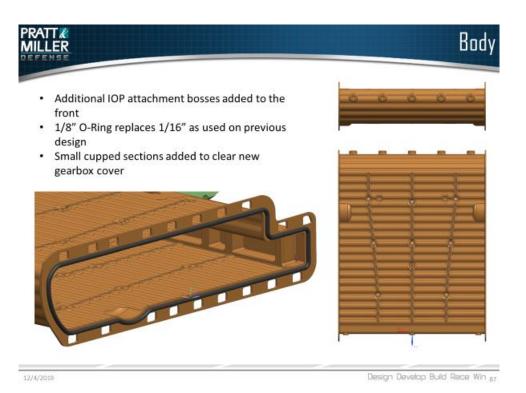


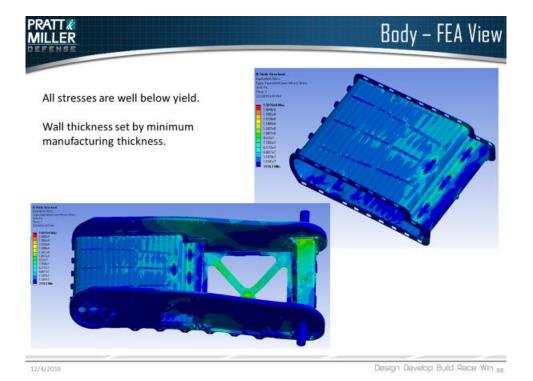
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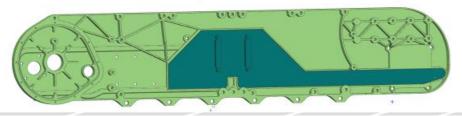




Side plates are modified with a larger 3/16" dovetail groove O-ring to seal both housings. The front housing is now secured with tapered pins and slide locks instead of 4-40 machine screws. The motor is interchangeable with the old or new gearbox.

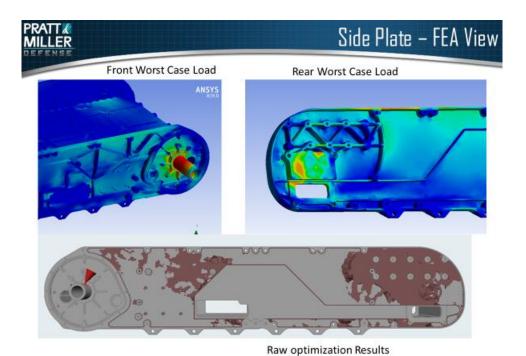


The circuit board connecting the front and rear electronics is unchanged.



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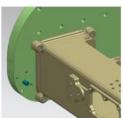
12/4/2019

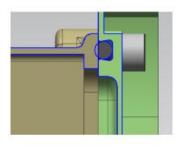


### Rear Crossmember Feature Updates:

- 1. 1/8" O-Ring and Dove Tail Seal
- 2. (4) 10-24 screws replace (8) 4-40 screws
- Add three ¼-20 base plate mount bosses

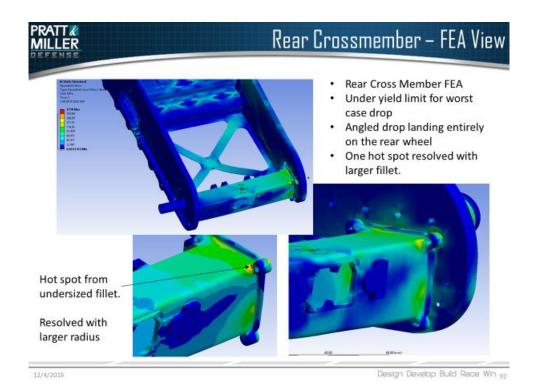








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## Appendix F – Build and Test Observations



### Print system and Alloy:

All parts were printed using a SLM M280 system and SLM recommended parameters.

The parts were stress relieved prior to removal from the build plate. The parts were then shot blasted for final cleanup.

Other than hand tapping threaded holes and painting the parts with CeraKote, no secondary steps were done to the parts.

The material, AlSi10Mg was also supplied by SLM.



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## FEATURE DESIGN, BUILD AND VALIDATION

### **Common Features:**

- 1. Joining
- 2. Sealing
- 3. Quick Disassembly
- 4. Spring Joints
- 5. Bore Tolerances and Alignment
- 6. Large, Thin Features Sheet Metal Replication

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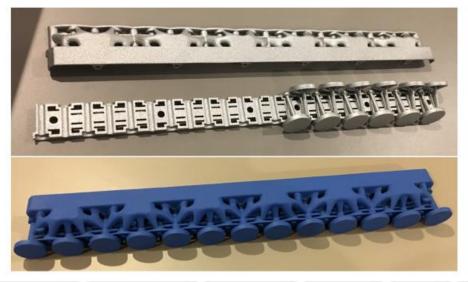
### **Printed Aluminum Wheel and Track**



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### SPRING JOINT ASSEMBLED AND WORKING







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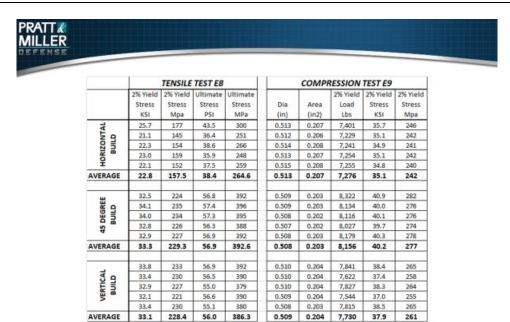


### Second system test: Flipper and Spring Joint



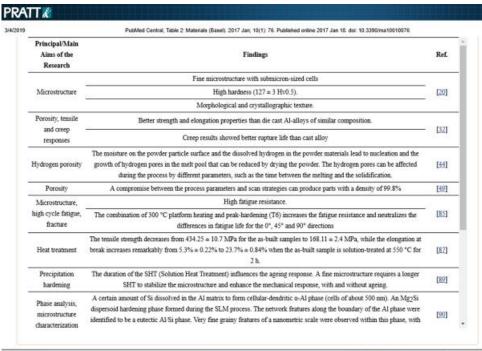
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## **Appendix G – Material Characterization**



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- Nima Shamsaei, Auburn (fatigue metalis)
   Tom Starr, Univ Louisville (static fracture metals)
   Diana Lados, Worcester Poly (fatigue metals)
   David Roberson, UTEP (fracture low-end polymers)

Steve Daniewicz (Univ Alabama) John Lewandowski (Case Western Res Univ) Ma Qian (RMIT Australia) Nik Hrabe (NIST) Li Yang (Univ Louisville) Brad Boyce (Sandia) Frank Liou (Missouri UST) Mohsen Seifi (ASTM) Chris Williams (Virginia Tech) Matt Frank (Iowa State U)