# Part 1: Table of Contents



# Part 2: Identification and Significance of the Innovation

<u>Identification of the Proposed Innovation</u>

Uneven and unpredictable terrain conditions present a variety of challenges for autonomous robots. To date some of the most popular robots to successfully navigate unpredictable terrain are the series of mars exploration rovers (or MERs) from NASA, see fig 2 section 10. The MERs make use of a 6 wheeled rocker bogie suspension system which allows each wheel to have a different elevation. As a result, the Ave average position of the wheels orients the MER body to a stable position.

Stability of the rover body can be interpreted in terms of the rotation angles of the rover's center of gravity (or COG) achieved on the xy, xz, and the yz planes, see fig 1. Whilst other parameters may be considered components of stability, ultimately the goal is to achieve values on all three COG parameters such that the COG is positioned at a desirable elevation relative to the ground and acting against the direction (or gradient) with the highest chance of tipping over the rover.

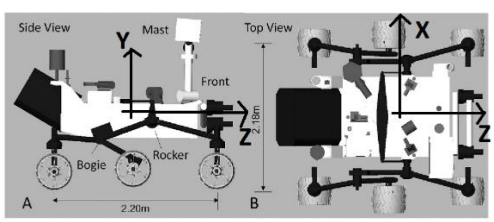


*Figure 1*

While the MERs indeed have a high degree of stability, they only have active control of their XZ COG angles, with passive control of their XY and YZ parameters, see fig 1. As a result of this, the exploration range of the MERs is limited. This presents an opportunity to expand the range of exploration by increasing stability. One example of this was implemented on the spirit and opportunity rovers:

extending the rear wheels thus making each bogie longer and moving the cog. By doing so, the MERs were able to navigate steeper slopes. However, another example of this is a walking robot. Walking robots inherently have greater control over their COG parameters. Legs on a walking robot not only allow for increased mobility on unpredictable terrains, but I. fact due to the various degrees of freedom legs indeed allow for optimal control of COG parameters.

The primary goal of this proposal is to greatly increase rover stability thus potentially allowing for in depth navigation of craters and other areas of interest with steep slopes. In order accomplish this, we propose the following innovations:

1. To incorporate an active suspension system. This system would allow the rover using it to navigate unpredictable terrain more like an off-road vehicle would on Earth.
2. To incorporate walking functionality into the suspension system. Walking would indeed allow the rover to achieve greater stability while rolling its wheels on the terrain. This walking functionality would create a hybrid wheeled-limbed suspension system.
3. To actuate this hybrid wheeled-limbed suspension system electromagnetically. By doing so we can remove the limitations of traditional suspension systems implemented on commercial vehicles on Earth, see fig 3.

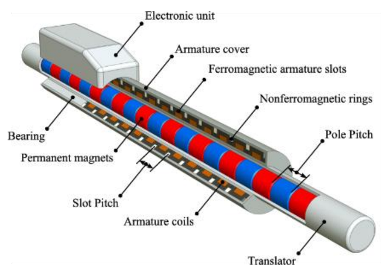

*Figure 2*

In summary, the proposed innovation is to develop an electromagnetically actuated hybrid wheeled-limbed suspension system. The remainder of this proposal will go over the feasibility of the proposed innovation.

Significance of the Proposed Innovation

The proposed innovation is a response to subtopic S4.02 – Mobility, Manipulation, and Sampling, of focus area 4 – Robotic Systems for Space Exploration. 508 Industries LLC is primarily focused on robotics research and development, and therefore this subtopic is directly in the line of the sight of the company's mission objectives. As NASA continues to expand its efforts in space exploration, "future missions may rely on co-located and distributed teams of robots and humans", as stated on the description of Focus Area 4. Specifically, the mobility needs within subtopic S4.02 outline NASA's interest in exploring environments on places like Mars, the Earth's moon, Europa, where the surface consists of rough, difficult, and unpredictable terrain. Additionally, this subtopic identifies the need for various types of mobility systems such as limbed, wheeled, and aerial systems.

Specifically,
The proposed innovation is of significance to NASA and its missions in that it allows for the exploration of craters beyond current surface level missions. This is due to the dual mobility hybrid wheeled-limbed systems. As such, sending a rover deep to the bottom of a steep crater would not prevent the rover

from exiting the crater once a mission there is completed. In steep slopes, the proposed innovation allows the rover to adjust its COG parameters as well as transition from driving to walking mobility.

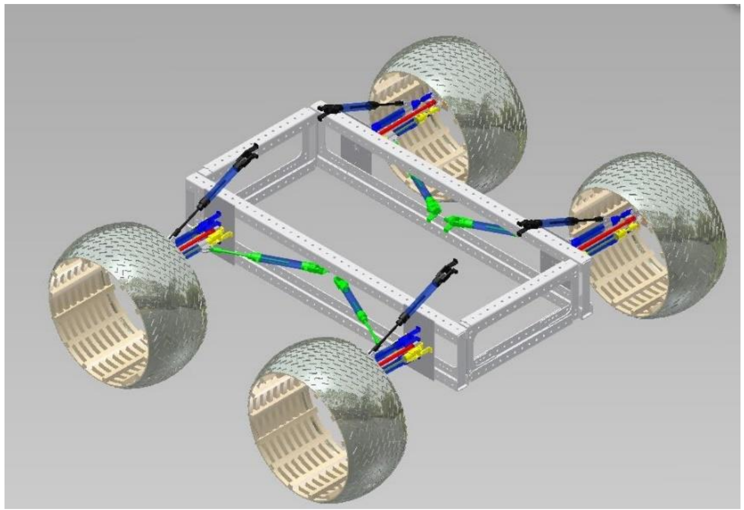

*Figure 3*

Proposed innovation relative to the state of the art

While there are several implementations of wheeled-limbed mobility, these systems are less efficient by having components that are always not used. The following are some examples:


Hyundai, Cradle Walking Car Concept 2019 (1); German Research Center for Artificial Intelligence, SherpaTT robot 2018 (2); Boston Dynamics, Handle Robot 2017 (3); Max Schwarz, Tobias Rodehutskors, Michael Schreiber, & Sven Behnke, Robot MoMaro 2016 (4); Ali Sadeghi, Alessio Mondini, Emanuela Del Dottore, Kumar Mishra, Barbara Mazzolai, Soft-Limbed Wheel-Based Robot 2016 (5); Boston Dynamics, RHex Robot 2012 (6); Carnegie Mellon University, Scarab Rover 2010 (7); NASA, ATHLETE Rover 2009 (8); NASA, Mars Rovers Soujourner 1997 (9); Spirit & Opportunity 2004 (10); NASA, Curiosity Rover 2011 (11)

In relation to the state of the art, the proposed innovation stands out in that it uses a suspension system to achieve hybrid wheeled-limbed mobility. By doing so, the rover doesn't have to carry with it components that are only used when needed. For example, in figures 1 through 4 the robots have several motors and associated sensor components which are not continuously used to achieve mobility. Therefore, when walking for example the wheels do nothing and vice versa. While its not necessarily clear how significantly this feature affects the overall efficiency of the robot in terms of power consumption for example, it does make the robot more complex. The more complex the robot is in terms of unique number of parts for example, the more opportunities for failure there are. In a remote difficult and dangerous environment, such as the surface of the moon or a crater on planet Mars, this could mean the robot is stuck. The proposed innovation mitigates this by employing an electromagnetically actuated system which reduces the need for unique number of parts and therefore simplifies the robot significantly. Additionally, the proposed innovation removes contact between some of the moving parts therefore reducing overall wear and tear on the robot and thus increasing its life.

## Part 3: Technical Objectives

Feasibility in terms of Goals

The primary objective is to develop an electromagnetically actuated hybrid wheeled-limbed suspension system. When completed, the proposed innovation should meet the following goals:

1. actively maintain cog control in terms of xy, xz, yz plane rotation angles, wheelbase and ground clearance parameters to achieve greater stability and maneuverability.
2. seamlessly transition between driving and walking functionalities.
3. minimize the number of unique components or select components capable of multiple functionality.

Feasibility in terms of Constraints and Issues

While researching the proposed innovation in preparation for this proposal, several issues arose requiring the consideration of the following constraints:

1. The estimated cost for an electromagnetic actuator along with sensors, speed controllers, and other packages components was found in the range of $15,000 to $20,000 per package. Lower cost vendors were found to have little or no support for their products (ie: accompanying software, warranties, or tech support).

2. All vendors required client provided specs in order to provide custom developed solutions rather than off the shelf components. This became especially difficult considering those specs would have to be determined during execution of the project. Also, sales representatives became part of the process making it very difficult to discuss specific details. This led to unclear and wildly changing cost estimates.

3. Considering several electromagnetic actuators will be required for the development of the proposed innovation, the cost estimates would consume most of the budget leaving little or no room for materials, subcontractors, overhead, administrative and direct costs.

4. Due to schedule, budget, and the afore mentioned limitations, it is proposed that the electromagnetic actuators be constructed in stages, and before any other work starts. The first stage will involve building one modular actuator into a modular testing fixture and adding to this all the accompanying sensors and controllers needed. The purpose of this stage is to have a platform on which to try out different designs. The second stage will involve building 4 actuators and an early prototype of the suspension arm with linkages and other components. This will allow for 1 of the 4 suspension arms planned in this project to be tested in its own fixture to further identify design parameters for the actuators and the suspension arm and linkages. As soon as 2 design options are identified, we need to build 4 suspension arms a chassis to which we'll attach the arms, and a testing fixture. From there we will test the entire system to test various programming options to achieve walking, driving, and steering functionality.

5. Any redesign or rebuild resulting from full system testing, will happen next. At this point unless a failure occurs or inefficiencies are found, it is expected that only programming changes will continue as the team tweaks the project to optimize for cog control and stability. Note that the first electromagnetic actuator and the first suspension arm may end up being rebuilt during this part of the project. Therefore, by modularizing these components the team may expect to reduce the number of rebuild iterations and potentially incorporate these into the final design. It should also be noted that this partial testing process will happen parallel to the design process. Ideally redesign and testing will allow for the most efficient path towards achieving the goals above whilst for the identification of a feasible version of the proposed innovation.

Feasibility in terms of Objectives

As per the list above, the team will have the following objectives:
1. Build a modular electromagnetic actuator (1-2 weeks)
2. Build a partial test platform for said actuator (1-2 weeks)
3. Build 4 modular electromagnetic actuators, suspension arm, linkages, and other components needed to test one suspension arm (2-3 weeks)
4. Build a test platform for said arm that (2-3 weeks)
5. Build 4 suspension arms, a chassis, and assemble them (3-4 weeks)
6. Build a full system test fixture (2-3 weeks)
7. Optimize and tweak programming functions and parameters while testing full system (6-8 weeks)
8. Demonstrate proposed innovation and make recommendations for phase 2 (1/2 - 1 week)

Expected Outcomes and Deliverables

Throughout the project, it is expected that the team will submit weekly or biweekly progress reports along with pictures, videos, technical drawings, expense reports, time sheets, any design changes, changes to the schedule and budget, updates to goals and objectives, and observations for feasibility.

## Part 4: Work Plan

Technical Approach & Method

In order to successfully achieve the objectives described in part 3 of this proposal, 508 Industries LLC, has divided the project into the following major work items:

Task Descriptions & Work Breakdown

During phase 1, our team's efforts will focus on designing and building a proof of concept for ATMEV.

Meeting the Technical Objectives

ATMEV meets the technical objectives outlined in part 3 as follows:

Task Labor Categories & Schedules

Table 1 provides our projected allocation by labor category by task.
Table 2 provides our projected schedule by task.

Budget appropriations

As the

## Part 5: Related R/R&D

The body of work related to the proposed innovation includes a rope climbing robot (2017), a modular robotic arm (2016), a lightweight drone (2013), just to name a few. The key innovations in these projects included a hybrid chassis-drivetrain system for the rope climbing robot (2017), a universal multifunctional module for the robotic arm (2016), a lightweight flexible aluminum frame for the drone (2013).

The first time Jed worked on an all-terrain robot, was back in 2008 as part of an undergraduate research project in college. At the time, the goal was to present an innovative design which would highlight the existing capabilities of the Mars exploration rovers at the time and show how these rovers could not engage the unpredictable terrains of other worlds, such as planet Mars, at high speeds. As the research went on, Jed learned about the various suspension systems used in modern vehicles for commercial and industrial traffic on Earth, and the limitations that these systems presented to the exploration of unpredictable terrains. As Jed learned more about the rocker bogie suspension system employed by the mars rovers, Jed began to understand why these systems were chosen but also why they were limited. In short, the rocker bogie suspension system coupled with a harmonic drive allows for the mars rovers to safely "crawl" their way through the unpredictable environment they are in while keeping the robot relatively stable and safe. Though the slow speed of these rovers allows for thorough scientific studies of the environment, they are not suitable for high speed traversal of said terrain.

In addition to this research project, Jed also studied several other projects which had similar objectives and design criteria. While some robots present a primarily limbed locomotion system with wheels attached at their ends, these robots are not ideal for high speed traversal of unpredictable terrains because the vibration loads could cause damage to the legs and therefore would present considerable engineering challenges which could be solved with a different approach. Moreover, Jed also explored robotic designs which included both wheeled and limbed systems which were separate from each other. In this case, these robots were meant to allow a transition or "switch" between locomotion systems such that the robot would not have to be limited by the design constraints of one system. However, these systems unfortunately require the robot to carry the mass of each locomotion system even though those systems are not in continuous operation. As a result, the robot would have to dedicate both power and mass to carrying these "dead loads" or otherwise unused components. Though power consumption could be made efficient enough to justify carrying the added mass, the system would not be low mass and would be considerably more complex. Lastly, Jed explored hybrid systems, which presented either a primarily limbed-wheeled hybrid or a primarily wheeled-limbed hybrid suspension system. In the case of a primarily wheeled-limbed hybrid suspension system, the robot is a lot more like a vehicle in that it'll have a suspension system with the added capability of walking using said system.

Based on Jed's research, this type of mobility system is not only ideal, but in fact a perfect response to NASA's mobility needs, as outlined in subtopic S4.02. This is because having a suspension system allows a vehicle to traverse the terrain at high speeds since the system would negotiate the resulting loading conditions. Specifically, the proposed innovation is a hybrid wheeled-limbed leaning suspension system because as such, the system in this configuration can carry out multiple functions without additional sub-systems or complimentary systems, and it would do so in a simple and seamless transition between functions. Moreover, during his research project in 2008, Jed learned about leaning suspension systems. A type of semi-active suspension system which was developed in response to poor stability conditions during high speed maneuvers such as cornering. Specifically, Jed realized that a semi-active leaning suspension system could be converted into a fully active suspension system by replacing its shock absorber with a hydraulic actuator and replacing the A-arms with beams mounted on a turning post and actuate the turning motion of said post using additional hydraulic actuator. This was how I planned on allowing the robot to “switch” into a walking function, while using the same components as a suspension system whenever the robot “switched” back to its driving function. Fast forward to 2018 and Jed found electromagnetic actuators such as brushless linear motors and voice coil actuators, which could both significantly simplify the design of the system and significantly reduce its weight. Lastly, it should be noted that while Jed conducted undergraduate research on the project, he never received any funding for it. This was in part due to the limited availability of undergraduate research funding at New York City College of Technology. Specifically, Jed was able to participate in robotics projects with similar objectives to project ATMEV. However, based on estimates, Jed was not able to pursue project ATMEV due to funding requirements exceeding what the college had available at the time. Additionally, Jed did not incorporate 508 Industries LLC until February of 2017, again this was due to Jed’s limited personal finances. In the time since the research on ATMEV had been conducted, Jed worked at various organizations as a mechanical design engineer. However, these organizations did not have an interest in project ATMEV.

The research noted above was done in parallel to several robotics project by Jed and in some cases by Jed, the team members, and others collectively. The projects were mostly inspired by NASA’s mars exploration rovers (MER) Spirit and Opportunity. The goal of these projects was to explore variations of the rocker-bogie suspension system employed on the MER’s in order to identify potential improvements. For example, removing the differential located at the center of the rover, led to the development of Flexbot in 2010. Flexbot employed a “simple” differential, in that the wheels were attached in pairs to 2 beams, whilst the 2 beams were themselves connected both at their centers to a third beam with a single bar that allowed the beams to rotate about said bar and at their ends with a single bar which limited the rotation of the beams. This caused the third beam in the center to maintain the average position of all the wheels to ensure stability.

## Part 6: Key Personnel and Bibliography of Directly Related Work

In 2017, 508 Industries LLC completed the proof of concept development of a modular robotic arm for desktop applications. The goal of the project was to provide an expandable low-cost multifunctional unit. The project was initially developed for internal use within 508 Industries LLC. The long-term plan is to develop a small low-cost automated manufacturing and assembly system that utilizes multiple arms each able to swap various attachments and manipulate various components for future product development at the company.

Jed Ferreras is the owner and CEO of 508 Industries LLC. Throughout this project, Jed will serve as Principal Investigator, and will be extensively involved in all areas of the project. Jed is a mechanical design engineer whose career and work spans 13 years across several industries including façade design, structural design, robotics design, machine design, and more. Of specific interest to the proposed innovation, Jed had previously participated in the Mechatronics Technology Center (MTC). MTC was a center for technology education, where Jed and colleagues worked on the development of various robotics projects. In addition to this, Jed has served as a mentor, referee, designer, and inspector for the High School First Robotics Competitions (FRC) since 2007. Jed is committed to the future growth and development of 508 Industries LLC, its mission and the proposed innovation.

Jed has worked on multiple robotics R&D projects, such as:

- Robot Chloe – Elevator/Lifting Robot, FRC 2018
- Robot Bridget – Rope Climbing Robot, FRC 2017
- Robot Mori – Modular Robotic Arm, 508 Industries LLC 2015-2017
- Quadcopter – Lightweight aluminum-polymer composite drone, MTC 2013-2014
- Candy Crane – a modular candy delivery crane, MTC 2011-2012
- Flexbot – a passive suspension system concept, MTC 2009-2010
- ATMEV – an all-terrain suspension system concept, Jed 2007-2010

## Part 7: Potential Future Applications and Relationship with Future R/R&D

Indoor Environments and Catastrophe Site Applications

Currently a common application for hybrid wheeled-limbed suspension systems is in the autonomous navigation of both indoor environments and catastrophe sites. Indoor environments while typically predictable and consistent in the nature of the terrains they present, often have several obstacles and changes to said terrain. Going up and down stairs, avoiding static objects such as structural columns and furniture, navigating around people which themselves are moving, are some of the typical scenarios presented to a robot. Catastrophe sites often have uneven and unpredictable terrain conditions like those found in space. Places where buildings and major roadways have collapsed often leave debris and craters in the ground. These environments can often be inaccessible and dangerous to humans.

In both indoor environments and catastrophe sites, there are humans working who could often find themselves distracted with mundane tasks such as carrying items to various indoor locations or removing dangerous debris both of which could be handled by a robot.

Potential NASA Applications

The proposed innovation presents a unique opportunity for NASA: A single system capable of multiple forms of mobility far more efficient than the current state of the art and with significantly less wear and longer life. This type of system is ideal for deep crater exploration, areas where ice may be found, and other extreme environments. The resilience and capability of the proposed innovation can be applied to a wide variety of missions including deep sea exploration. Thanks to the electromagnetically actuated feature of the system, it doesn't require lubrication or tight tolerances to operate and therefore can tolerate the conditions of deep-sea explorations such as exposure to water, potentially high salinity levels, and more. If this system is equipped with contactless or compliant joints, its resilience would outperform any existing mobility system currently in development. Specifically, these types of joints would be ideal for limbed locomotion on the surface of the moon where rovers would be exposed to the shearing and otherwise extremely destructive effects of lunar dust. Whilst this proposal is purely focused on the proposed innovation, there are several additional technologies of interest such as compliant joints which could be explored and applied together with the innovation explored in this proposal during phase II.

Phase II R&D and Commercialization

508 Industries LLC's final report will demonstrate to NASA our total commitment to the development and marketing of the proposed innovation as a product. 508 Industries LLC perceives the Phase I work to be a demonstration of a prototype of the major innovations identified in Part 2 of this proposal. 508

Industries LLC envisions Phase II work to encompass the building of a full commercial product with associated production quality technical and user documentation.

This effort is to form the basis of a product that 508 Industries LLC brings to market. At the start of Phase III, 508 Industries LLC, plans to either finance its initial operation with venture capital, or if no venture capital is obtained, the principals are committed to self-finance the venture during Phase III. The NASA SBIR programs itself will serve as the initial beta site for 508 Industries LLC's product.

Additionally, the intended commercialization method for the proposed innovation is to offer a subscription or rental service where units are not necessarily owned by customers but rather temporarily rented. This way especially in its autonomous mode, the system could be used and operated remotely by both NASA and NON-NASA customers through a website or app. Though the interface is not yet in development to grant remote access, the goal is to utilize this system to enable access to space via a series of units deployed at various locations throughout the solar system using the internet. In this manner, the proposed innovation could be used for planetary exploration, remote In-Situ Resource Collection (ISRU), mining, among other such functions. Lastly, 508 Industries LLC also intends to make the proposed innovation available to future Lunar and Martian explorers in a similar fashion.

It is important to note that currently there is no commercially available option for remote space exploration. At the moment it is not possible for people outside specific space mission programs such as the Mars Rovers, to gain access to these systems and the capabilities they provide. It is part of the mission at 508 Industries LLC, to enable access to space using remotely operated robots deployed at various locations via a website or app or other software technology. During phase II, if funded or after, 508 Industries LLC, will begin the development of a dedicated web application and desktop/mobile app for remote access to interplanetary robotic units.

## Part 8: Facilities/Equipment

Location

In order to successfully achieve the objectives of the proposed innovation, this project will require access to at least desktop size 3d printing, waterjet cutting, and potentially cnc milling equipment. At the moment, 508 Industries LLC is located in Brooklyn, and currently rents a residential space. All 508 Industries LLC operations take place in this location, all consultants, all shipping, and otherwise critical functions will take place there.

Computers & Software

508 Industries LLC currently has access to fusion 360, Autodesk inventor, and Eagle CAD software for structural, mechanical, and electrical design work. Additionally, 508 Industries LLC will be using python 3.7 for software development work.

Equipment

508 Industries LLC will require purchase of desktop sized waterjet, 3d printers, and a cnc milling machine, which have been specified in the budget. Specifically, 508 Industries LLC will require the use of a Wazer desktop waterjet for most of the production of parts during this project. Additionally, a Lulzbot

Taz Workhorse 3D printer for complex components, and a Pocket NC V2-10 5 axis desktop milling machine for precision components.

Wazer Desktop Waterjet

Wazer is a cnc waterjet machine capable of cutting various metals including steel (up to 3/16" thick), aluminum (up to ¼" thick) and more. As per the 12/9/2019 quote (#D2980), the machine costs $9,999, fees and taxes for the state of New York are $887.92, totaling $10,886.42.

Lulzbot Taz Workhorse 3D Printer

Lulzbot Taz is a 3D Printer with a build platform roughly 11" x 11" x 11.2" or 1300 cubic inches. The layer resolution is 0.002 – 0.020 inches, and is compatible with PLA, ABS, Nylon, Polycarbonate, Carbon Fiber Reinforced Blends, TPU 85A & 95A (Flexible), PETG, PETT, Copolyester, PVB (Polycast), PVA, HIPS, and many more 3rd party filaments. As per their website, the machine cost is $2,950 all fees included.

Pocket NC V2-10 5 axis cnc

Pocket NC is a 5 axis cnc machine with a spindle speed of 2,000 to 10,000 rpm and is compatible with tool diameters up to ¼". The machine has a build size of roughly 4.55" in x, 5.00" in y, and 3.55" in the z axis, and can work with aluminum, steel, delrin, and various types of wood. As per their website, the machine cost is $5,999 and shipping is $70, totaling $6,069.

## Part 9: Subcontracts and Consultants – Computer Engineers

During the development of the proposed innovation, the following consultants have been identified to support the P.I. and the project:

Aidan Murphy – Subcontracted Computer Engineer

Aidan Murphy is a computer engineer with extensive experience in electrical design, breadboard testing and prototyping, microcontroller specifications, and programming. Aidan has worked extensively on various robotics programming projects. Like Jed, Aidan participated at the Mechatronics Technology Center (MTC) and First Robotics Competitions (FRC). As a technical expert, Aidan will be responsible for implementing various electronic subsystems for the project, and programming. Aidan is willing to devote up to 8 hours/week on this endeavor.

Eric Tung – Subcontracted Computer Engineer

Eric Tung is a computer engineer with an extensive background in low-level Embedded Systems and controls Programming, higher-level Kinematics, Mapping, Localization & Path-Planning algorithms. Like Jed and Aidan, Eric also participated in MTC and FRC. Eric architected & built the initial electrical prototype & web application for an Internet of Things-enabled medical device. Eric is willing to devote up to 8 hours/week on this endeavor.

## Part 10: Essentially Equivalent and Duplicate Proposals and Awards

Proposals submitted by 508 Industries LLC to request funding have not yet been selected for an award. 508 Industries LLC has not received any government award for work related to the electromagnetically actuated hybrid wheeled-limbed suspension system it is currently developing. 508 Industries LLC has not received previous SBIR awards from NASA or other agencies. 508 Industries LLC's proposed Principal Investigator (P.I.), Owner, and CEO has never worked for any government agency, or other organization receiving NASA or other SBIR participating agencies' funding.

508 Industries is however, planning to submit several SBIR Phase 1 proposals to both NASA the National Science Foundation (NSF) throughout 2020. These proposals are for different projects of interest to 508 Industries LLC. The proposed P.I., the facility, and the proposed sub-contractors for the proposed innovation discussed in this project will also be proposed for other proposals. Specifically, proposals S4.02-xxxx and S4.02-xxxx. For more details about the budget and schedule for this please refer to section 4.x.x. Additionally, the information on parts 5, 6, 8, and 9 is very similar specifically because the team and facility proposed for these proposals is the same.