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Improving the Electromechanical Reliability of Unmanned Ground Vehicles

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Abstract

The purpose of this report is to examine potential methods of improving the reliability of electromechanical components of unmanned ground vehicles (UGVs). The report begins with a brief overview of what a UGV is, how UGVs are used, how often they fail, and why they fail. This is followed by a literature review initially focused on methods to improve the design for reliability of robots and UGVs. The literature review then broadens to include how reliable design methods have been applied to other industries and how these techniques could be modified for UGV applications. The report concludes by examining a handful of simple proposed solutions to problems with current UGVs, including a method where springs are incorporated into robotic joints to improve strength, reliability and power consumption.
Introduction

Unmanned ground vehicles (UGVs) were once seen only in a hobbyist’s garage. Today they are being used more and more for a variety of commercial and military purposes. They are frequently used in the military, or by emergency responders, to go places that are inconvenient, too dangerous or impossible to reach directly. Their uses and designs vary greatly. Vehicles have been designed to go places where humans cannot such as hundreds of meters down oil drilling pipes to inspect wells. Unmanned ground vehicles were used extensively to help rescue workers search the rubble of the World Trade Center [1]. The famous Spirit and Opportunity rovers are exceptional examples of unmanned ground vehicles that remotely wandered the Martian surface collecting large amounts of data that will likely be examined for years to come. At the presidential inauguration in February, UGVs were driven underneath every bus to check for bombs. UGVs have also played a larger and more important role in the armed forces in recent years; with over 5,000 currently deployed by the US Army [26]. In Iraq and Afghanistan, UGVs of a variety of designs are used to inspect potential improvised explosive devices (IEDs), caves and buildings [2]. Hundreds of soldiers are alive today because a UGV found or detonated an IED instead of a soldier [26]. In every one of these examples, UGVs were used to accomplish something that would have been impossible or extremely dangerous for a human to do.

What exactly is an unmanned ground vehicle? A report by Nguyen, Huu & Titus provides an excellent overview of UGVs and how they fail [3]. A UGV can broadly be described as mechanized equipment that moves on the ground that does not carry a human being [4]. If the UGV contains sensing equipment and is capable of interacting with its surroundings it could be considered a ground-based mobile robot [5]. UGVs that we will be considering in the remainder of this paper fall into this category. UGV designs can vary greatly depending on the intended function of the machine. However, in general a UGV is comprised of the following subsystems [6]:

Sensors: Sensors allow the robot to perceive its environment. Proper perception of the UGVs surroundings is essential for reliable, effective and safe operation.

Platform: This is essentially the electromechanical part of the UGVs and is analogous to the skeleton and muscles on an animal. The platform provides the power, locomotion, structure, and physical utility for the UGV.

Control: How the robot perceives its surroundings and follows human commands is a function of controller design. Designs vary widely – they can be as basic as a design that lets the human controller interpret all sensor data and then follow the human instructions exactly. On the other extreme, a controller could be built so that the UGV operates autonomously for extended periods – interpreting its surroundings and making decisions on its own.

Interface: How the robot interacts with human commands. UGVs often have many degrees of freedom and depending on the control system, every one of them may need to be controlled by the human.

Communication: How the robot sends and receives information is very important. If the robot is operating within range of a base, a fiber optic cable could be used. However, cables can snag on things and limit the range of the robot. In the case of military robots, wireless communication is necessary. Furthermore, the data must be both accurate and privileged.
System Integration: The configuration of the overall system. Increasingly well designed robotic systems will become more reliable and therefore able to operate more autonomously.

Reliability Issues with UGVs and Common Failure Modes

Because UGVs are a very young industry and generally operate in uncertain environments they suffer from a number of reliability issues. This is very much in contrast to aircraft and automobiles – both decades old industries that not only put a premium on vehicle reliability, but also have optimized their vehicles for very specific operating conditions. In many ways UGVs are in a place now that computers were twenty years ago. Like computers twenty years ago, the early history of UGVs occurred mostly by hobbyists. If their computer/UGV broke, a hobbyist would open it up and use whatever was convenient as a method to fix the problem. Furthermore, they could perform these repairs whenever they wanted. This is not considered acceptable in any industry. People would never buy a car if it broke down every other week of routine driving, and people would certainly never board an airplane if it broke down after a few flights. UGVs have not yet developed this level of reliability, in fact, they break down frequently.

Technical papers authored by Carlson and co-workers are some of the most extensive works on the reliability of UGVs to date. Carlson’s thesis [5] summarizes and includes the data collected and published in three previous papers [7][8][9]. These papers describe both how often UGVs fail and in what manner. One particularly useful piece of information to gauge reliability is the mean time between failures (MTBF). Table 1 shows reliability statistics for three robots in both an initial study (top) and follow up study (bottom.)

<table>
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<th>Manu.</th>
<th>Type</th>
<th>% of Usage</th>
<th>MTBF(hrs)</th>
<th>Availability</th>
<th>Ave. Downtime(hrs)</th>
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<td>90%</td>
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<td>149.08</td>
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</table>

Note: % of Usage is the percentage of total time that the robot was used in fields.

Table 1. Summary of results from CRASAR Reliability [9]

A major conclusion of the Carlson study is that the MTBF is usually between 6 and 20 hours. This was also corroborated by anecdotal comments during our visit to the US Army Joint Robotics Repair and Fielding (JRRF) facility in Michigan. This would not be a large problem if UGVs were only owned by hobbyists, who could fix them whenever they wanted or had the time. This is no longer the case and it becomes less so every year. Every year the army deploys more and more UGVs (figure 1). These vehicles are placed in admittedly difficult environments, but rarely last more than twenty hours of active duty before requiring some form of maintenance or repair. When these vehicles are being repaired they are not in the field of duty where they are needed to assist soldiers.
Furthermore, as more UGVs are deployed, each UGV technician will have more work to do, as there will be more vehicles needing repairs at any given time.

Figure 1: Improvements in military UGV reconnaissance, and the dramatic increase of UGVs deployed in recent years [10].

Qualitative Comparison Between Army UGVs and Mars Rovers

Interesting examples of UGVs that have shown to be reliable well beyond anyone’s expectations are the mars rovers, Spirit and Opportunity. It was hoped that the rovers would remain functional for a three month mission. Amazingly, both rovers lasted for multiple years! The obvious question then is: why have these UGVs worked for years, while the average one can only last for a dozen hours without breaking. There are many answers to this question. First of all, the mars rovers were designed from the ground up for the very specific mission of exploring the Martian surface [11]. This is a major contrast to the Talons and Packbots being used by the US Army, which are off the shelf vehicles, with a few customizable features. Second, because there is no way to repair the rovers on mars, the remote handlers are extremely careful with them [12]. They know exactly what the robots are capable of doing and a very careful to make sure that the robot never does anything it was not built to do. Army UGVs do not experience this form of care. Operators will routinely operate the robots in a way that pushes the robot beyond what it was designed to do. This can happen intentionally (trying to lift something that is too heavy) or by having difficulty using the UGV interfaces. NASA mission controls have hours to make decisions and plan the rovers’ next move. Army UGV operators have to make those same decisions in real time. The Mars rovers also have also been able to take advantage of redundant systems. Despite losing control of a wheel, NASA engineers found that by running the rover in reverse it could still be maneuvered. If an analogous situation were to occur in a Talon or Packbot, the operator would not have time to come up with a workaround solution and would instead take the robot to a maintenance facility.
No doubt, there are lessons to be learned about reliability from the mars rovers. Interfaces could be improved a lot, possibly using haptics, which would allow operators to control their vehicle more easily and have a better sense of the limitations of the UGV. Finally, the UGVs could be built with either redundant systems, or some sort of fall back system, so that when a part of the UGV failed, the vehicle would still be able to limp back. The UGVs could be designed more specifically for certain environments instead of the one size-fits-all approach that is currently used. The difficulty is in being able to implement these improvements without each robot costing as much as a mars rover.

Review of Literature on Reliability Relating to UGVS

One of the most daunting problems of improving the reliability of UGVs is the complexity of the system. Each subsystem is complicated and can suffer from a lack of robustness in its design. If any of the numerous subsystems fail, the UGV may be crippled and in need of repair. Because the general reliability problem is so complicated, it is essential to be able to break the problem down into more manageable pieces. In this section is I will only look at methods used to improve the reliability of the electro-mechanical design. To do this I will examine two general areas of the literature. First I will examine what research has already been done on the design and reliability of ground vehicles and robotic manipulators. The second area will examine some of the techniques used by other industries to ensure reliability in their products. There is an extensive amount of literature in this area, especially from the aircraft literature where reliability is of utmost importance.
Reliability and Design Techniques in the field of Robotics and UGVs

“Reliability-Based Design Optimization of Robotic System Dynamic Performance”

One of the major causes of failure in robotics is that the robot is not being used in a manner consistent with its design. One way this happens is simply due to uncertainty. Instead of starting with an exact configuration (certainty), reliability based design optimization (RBDO) represents that configuration by a probabilistic distribution. RBDO then looks at the solution over the probabilistic configuration. This information is often more useful than the solution to an exact configuration because in the real world things are never known exactly. It is important that the robot work over the range of uncertainty and not just one certain configuration.

Designers can predict the dynamic performance of a robot using the dynamic capability equations (DCE). These equations can be used to predict how the end effector of the robot can accelerate or apply forces and torques given a single configuration. Either of these descriptions (as well as several others [14][15][16][17]) could be used to describe the dynamic capability of the robot arm. The key limitation of this approach is that the DCE is only found for a single configuration at a time. By systematically performing DCE calculations for a large number of configurations that fill the feasible space, an overall measure of dynamic performance can be determined.

Alternatively, an overall measure of dynamic performance can be calculated by combining RBDO methods to the DCEs and using a probabilistic density function to characterize the feasible space [18]. This approach yields a number of advantages over testing many points within the feasible space. One advantage is that the number of feasible operational points will rise exponentially as the number of degrees of freedom increases. Evaluating enough points to adequately fill in this space would require immense computational time compared to a probabilistic distribution. Secondly, the solutions from a discretized approach can still miss the optimal values found by the RBDO approach. This is illustrated clearly in figure 3.

Figure 3. Contours of Optimal Torque Values [18]. Figure 3a was generated by taking samples within the feasible space and solving DCEs, yet misses the true optimum value found in figure 3b utilizing the probabilistic approach.
Utilizing the RBDO in this setting can also be used for the selection of actuator sizes. While a certain sized actuator would be required to achieve a certain dynamic performance at any point, it is generally not practical to have more than one motor per degree of freedom. The RBDO approach offers an effective, and conservative, way to view the entire operational space of the robot at once - providing an effective way to select actuators optimized for reliability. Results from Bowling’s paper confirm the expected result that larger motors would be required in a system optimized for reliability [18].

“Concept of Intelligent Mechanical Design for Autonomous Mobile Robots”

The reliability of robots can also be improved by utilizing the “concept of intelligent design.” [19] Nassiraei notes that all aspects of robot system are becoming more complicated and that future robots are going to have to be much more complicated than the robots of today in order to achieve their objectives. These complexities may lead to an increase in weight and power consumption, but will most certainly lead to a loss of reliability and an increase in cost. To mitigate these effects, the electro-mechanical system or platform must be kept as simple as possible. This approach, however, does not take into account the relationship between mechanical design and controllability. Ultimately, there needs to be a balance where the design has enough complexity to achieve a desired performance, yet remain simple enough to keep cost low and reliability high.

Nassiraei proposes the use Intelligent Mechanical Design (IMD), where IMD is a design that is “self-controllable, reliable, feasible, compatible … and solves the functionality-usability tradeoff in an optimal way.” [19] This can be formulated as an optimization problem. Self-controllability, reliability, feasibility, and compatibility essentially define a set of constraints on the design space. The curve of optimal solutions to the functionality-usability tradeoff is the same as looking at the Pareto set.

Nassiraei continues by tabulating a list of mechanical design principles (MDP). Although these are mostly common sense some are worth mentioning specifically and have been paraphrased here:

1) To design mechanical parts for a UGV, one has to know the environmental niche, the desired behaviors of the robot, and the design of robot mechanics (figure 4).

2) The mechanics (and sensors and actuators) must be complicated enough to perform the desired tasks, but not any more complicated than that.

3) Take advantage of the robots environmental niche.
These techniques are all good ideas to follow and should be utilized during the design of UGVs.

**Reliability Techniques from other Industries**

The robotics industry is very young and as such has not yet generated a very large volume of literature on reliability based design as applied to robotic systems or UGVs. This stands in stark contrast to the automotive, aircraft, or manufacturing industries. Therefore, this section of the paper will examine some relevant literature related to reliable design found in other industries and discuss how the techniques discussed could be applied to robotics.

Consistent utilization of reliable design techniques have made airplanes one of the safest ways to travel. Mavris describes how a robust design simulation can be used on an aircraft design to optimize the variables prior to the construction of a prototype. In the introduction to his paper, Mavris has a figure the captures the purpose of using a robust design.

![Figure 5. Improvements to the variation of the Lift to Drag ratio by using a robust design (Design 2) compared to a standard design (Design1.) [20]](image)

In simple design optimization an optimal value will be found for a function at an optimal point in the design space. However, if the design is not performing exactly at that optimal point there is no way to know how well the design is behaving. Furthermore, it is unlikely that the design will be operating at the precise optimal point due to potential variations arising from manufacturing, the environment, the operator or other sources. This is demonstrated in figure 5 by design 1. Design 1 is excellent at the exact middle of the operational range but its performance degrades considerably everywhere else. A robust design is one that might not be excellent at any point, but is acceptable at all points. Design 2 in figure 5 shows this type of behavior. Although, it is not quite as good as design 1 in the central region of operation, it is much better than design 1 in the fringes of the operational range. By examining the distributions on the y-axis of the figure we see that design 1 shows a large degree of variation, while design 2 is almost constant over the operational range. Clearly, design 2 is a much more robust design.

The main content of Mavris’s paper describes how an aircraft can be optimized by subjecting it to various realistic duty cycles. It is an optimization problem where the amount of fuel consumed needs to be minimized over a large range of possible flight paths, while at the same time satisfying all of the safety requirements and other design constraints [20]. Applying this technique to UGVs should be relatively straightforward. The biggest difference would likely arise from the fact that a UGV (unlike an airplane) would experience more sudden and intense interactions with the environment. This is simply the
nature of ground vehicles. It should be possible to take a UGV model and simulate it on a virtual bump course in the same manner as a military vehicle.

Another technique that could be useful for improving the reliability of UGVs would be incorporating derivative free methods into RBDO. Derivative free methods outperform optimization methods that utilize derivative information when the function being optimized has lots of local minima. A derivative method relies on going “downhill” until the optimal solution is reached. However, it can get stuck in a local minimum. If the problem has lots of local minima, it would be very difficult for a gradient approach to show global convergence. A derivative free approach will not get stuck in a local minimum. Rather it uses an algorithm to test different points eventually picking ones that are better than ones it is already at. A disadvantage of this method is that they cannot know if they are at an actual minimum and thus will terminate at a different location every time. Youn describes the benefits of using the Eigenvector Dimension Reduction as an algorithm to perform the derivative free optimization - specifically how it can be used to assess quality and reliability simultaneously without requiring more computational power [21]. These techniques could be useful in optimizing UGVs due to the highly nonlinear nature of non-holonomic ground vehicles and robotic manipulator arms. It is also possible (and commonly done in optimization problems) to perform a derivative free approach first and then use the results to perform a gradient based optimization. This way a true minimum can be determined that is very likely also the global minimum.

Compared to standard design optimization, RBDO can be extremely computationally expensive due to evaluating distributions instead of points. The situation is exacerbated as the system being optimized grows in complexity. UGVs are certainly very complex systems. Thus, it would be greatly beneficial if there was a method of performing RBDO in a way that was less computationally expensive. Du takes a multidisciplinary design optimization framework and utilizes both system and subsystem uncertainty analysis to estimate the mean and variance of system performance [22]. As a UGV is a prime example of a multidisciplinary system it is a perfect candidate for this type of approach.

These are just a few examples from the literature whose methods could be applied to improving the electromechanical design of UGVs. Some other promising resources include this paper by Sanchez [23], and two authoritative texts by Phadke [24], and Park [25].

Example Problems and Anecdotal Solutions

Based on interactions with members of the armed forces stationed at the JRRF and personal interactions with two commonly used UGV platforms I can say with certainty that there is a lot that can be done to improve the reliability of UGVs. According to the repair technicians at the JRRF, the most common causes of failure were electrical. In one UGV, this was especially true because of the abundance of loose electrical connections and the rats nest of wires. This problem is actually twofold: the wiring is subject to failure because of the large number of wire connections, and it is very difficult to repair the robots quickly because of how many wires there are. One solution to this problem would be to replace some of the wires with easily replaceable circuit boards. We also learned that the robots are routinely used beyond their design specifications and that some of this can be attributed to an inadequate human-UGV interface. Although operating either UGV got easier with more training it was much harder than operating a car and arguably more difficult than operating a helicopter. One major difficulty was that the UGVs had more degrees of freedom than it
was possible to control at any given time. The Talon has fewer degrees of freedom than the PackBot, which arguably made it easier to use. Another problem is that the operator had to control each joint independently as opposed to commanding the end effector to move and letting the UGV calculate the intermediate joint angles. Apparently, Army operators prefer controlling each joint as opposed to just controlling the end effector. I believe that these difficulties could be reduced by doing any combination of the following:

1) Implement a control system that allows for the simultaneous control of most (if not all) degrees of freedom.

2) Develop a control logic that is intuitive to the point that controlling the end effector is preferable to controlling each joint independently.

3) Create a haptic interface that allows the operator to feel when the arm is obstructed or at the limits of its motion.

Implementing these improvements should make it easier to operate a UGV which would in turn make it less likely that the UGV suffered because of inadequacies in the user interface.

The chassis of another UGV contains much of the sensitive electronics as well as the drive motors for each tread. Because water and sand can wreak havoc on electronics, the chassis is built to be waterproof, allowing the UGV to drive through puddles without short circuiting. However, this has the unfortunate side effect of not allowing adequate ventilation. The temperatures generated by the drive motors, electronics, and desert sun can make the UGV overheat, leaving it inoperable until it cools down. Although many solutions exist, two are relatively simple and cheap. The chassis has no internal temperature sensor. Adding one would give the operator a warning when the UGV was getting too hot. This would give the operator a chance to run the UGV less vigorously – or if that is not possible – have it move to a safe area where it can cool down. The other option would be the installation of heat sinks on the outside of the chassis. These could keep the electronics cooler without sacrificing the waterproof aspects of the case.

Another problem with this chassis design is that a dent in the case caused by the UGV running over a rock can short circuit the electronics. In a redesign, this problem could be taken care of using the type of RBDO discussed in the previous section. Optimization of the distance between the bottom of the chassis and the circuit board would take into account the dents likely to occur from operating on rocky terrain. In the meantime, a much cheaper workaround would be to add a thin layer of insulating material between the chassis and the electronics. This way, when a dent in the chassis impinges on the electronics no short circuiting occurs. These are just a few of the ways that the reliability of UGVs could be improved with relatively simple solutions.

**Opportunities for Future work**

One possible area for future work would be the implementation of springs in the joints of manipulator arms. Current joint design is controlled almost entirely by the torque output and dynamics of the motors. Although this keeps the dynamics of the system simple, there are a number of disadvantages to this approach. First, it is very easy for a motor to saturate when the arm collides with an obstacle. Even with non-back-drivable motors, a collision with the arm would send shocks throughout the robot. If there were a
spring in series with the motor, the spring could absorb a lot of the energy and isolate the rest of the robot from vibrations. This would increase the life of the motor and the reliability of the robot. Second, motors have the most difficult time lifting objects when the arm is fully extended because of the longer moment arm. If extending the arm also extended a spring in the joint, then the motor would be assisted in lifting an object by the force in the spring. Finally, the springs could be used to store and return power about a common configuration. This is analogous to the energy that is stored and released by your Achilles tendon while walking. This storage of energy could reduce the amount of power required to achieve the same performance, increasing the battery life of the UGV. Current research being done in kinesesthesiology regarding the interplay of muscles, tendons, and bones with respect to dynamics and energy would be an excellent source of insight into this type of manipulator configuration. Clearly simultaneously improving the strength, reliability, and battery life of a UGV is a goal worthy of further research.

References


