Modeling Risk Perception for Mars Rover Supervisory Control: Before and After Wheel Damage

Alex J. Stimpson
Humans and Autonomy Lab
144 Hudson Hall
Durham NC 27708
(352) 256-7455
Alexander.Stimpson@duke.edu

Matthew B. Tucker
Humans and Autonomy Lab
144 Hudson Hall
Durham NC 27708
(919) 402-3853
Matthew.b.tucker@duke.edu

Masahiro Ono
NASA Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive Pasadena, CA 91109
Masahiro.Ono@jpl.nasa.gov

Amanda Steffy
NASA Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive Pasadena, CA 91109
Amanda.C.Steffy@jpl.nasa.gov

Mary L. Cummings
Humans and Autonomy Lab
144 Hudson Hall
Durham NC 27708
(919) 660-5306
Mary.Cummings@duke.edu

Abstract— **The perception of risk can dramatically influence the human selection of semi-autonomous system control strategies, particularly in safety-critical systems like unmanned vehicle operation. Thus, the ability to understand the components of risk perception can be extremely valuable in developing either operational strategies or decision support technologies. To this end, this paper analyzes the differences in human supervisory control of Mars Science Laboratory rover operation before and after the discovery of wheel damage. This paper identifies four operational factors sensitive to risk perception changes including rover distance traveled, utilization frequency of the autonomous driving capability (AutoNav), terrain risk weighting, and changes in high-level mission planning. A resulting Rover Risk Perception Model illustrates how these operational factors relate to increased perception of risk. Based on these results, we propose aiding risk perception mitigation strategies such that risk can be appropriately anchored. Such strategies can include a change in system design including adding technology and decision support tools, or changing the training of operators who use the system.**

TABLE OF CONTENTS

1. INTRODUCTION 1
2. METHODS 3
3. RESULTS AND DISCUSSION 3
4. CONCLUSION 6
ACKNOWLEDGEMENTS 6
REFERENCES 6
BIOGRAPHY 7

1. INTRODUCTION

NASA's Mars Exploration Program is a long-term program that is leading the robotic exploration of the planet Mars [1]. The Mars Science Laboratory (MSL) Curiosity rover, part of the Mars Exploration Program, is the fourth rover that has been sent to Mars. The first one was a small, 11 kg rover named Sojourner that piggybacked on the Mars Pathfinder lander. The next two were Spirit and Opportunity, part of the Mars Exploration Rover mission, launched in 2003. Spirit was active until 2010, while Opportunity is still operational. Curiosity was designed to help collect data that can be used to assess the past or present capability to support microbial life. In short, Curiosity was sent to Mars in order to determine the planet's habitability [1].

The Curiosity rover left Earth on November 26th, 2011. Approximately nine months later, the MSL curiosity rover landed on Mars on August 6th, 2012. The official touchdown site is a location known as Bradbury Landing that is near Mount Sharp, all within the Gale Crater. Gale Crater was chosen because it was deemed to give the Curiosity rover the best chance to collect data that could be used to accurately assess the former habitability of Mars [1].

There were a number of reasons why Gale was chosen over thirty other potential areas. First, the crater is at a low elevation on the planet. It is known that water is subject to gravitational forces associated with differences in elevation. Therefore, the formation of such a geological structure could be due to water. Another reason why Gale was chosen was because of the presence of an alluvial fan in the crater. Alluvial fans are fan or cone shaped deposits of sediment that are formed by streams of water. Mount Sharp, the primary destination, is a mountain that is within Gale Crater. This mountain contains layers of sediment that contain clay and sulfites, which are known to form in water.

MSL Planning Operations

The main goal for Curiosity is to determine the habitability of Mars. To do this, a three-tiered planning structure was formulated for MSL that considered both how to move Curiosity from point to point but also how to do science exploration at each site of interest. This planning structure is organized based on how far into the future the operations are planned. The three tiers of the process are the strategic planning, supratactical planning, and tactical planning.

Strategic planning is the type of planning with the longest time horizon, meaning that this type of planning accounts for the longest time into the future. A strategic planning timeline

978-1-5090-1613-6/17/$31.00 ©2017 IEEE

could include anywhere between several weeks to several months into the future. Some the aspects addressed include planning science campaigns, long-term management of rover resources, and long-term management of rover constraints.

Tactical planning covers the shortest time horizon, occurring one sol into the future. A sol is a full day on Mars, roughly a half of an hour longer than a typical day on earth. The tactical planning process is highly reactive in nature, and responds to data received from the rover on the most recent sol, in order to plan for the next proceeding sol.

During the prior two rover missions (Spirit and Opportunity), only strategic and tactical planning processes were utilized. However, that two tier planning architecture was not sufficient for this mission. For the current missions, MSL needed to adapt by utilizing the reactive nature of tactical planning, while simultaneously maintaining an expansive suite of complex instruments used to gather data. Some of these instruments require multi-sol campaigns in order to collect complete data sets [2]. Therefore, the supratactical planning process was created for MSL in order to address the insufficiency of the typical planning paradigm utilized in the first two Mars surface missions [2].

The supratactical planning horizon is shorter than the strategic planning process, but longer than the tactical process. This planning process bridges the gap that exists between strategic planning and tactical planning. This planning process incorporates certain aspects of predictive planning, as well as reactive planning. Supratactical processes help develop the upcoming rover plans by accounting for known operational constraints and allowing the planning team to identify potential risks, uncertainties, and opportunities in future plans. The next section will discuss select pieces of hardware associated with the rover. Specifically, cameras that help provide visualization for the terrain and the wheels of the rover.

Curiosity Cameras

MSL utilizes two types of cameras for the generation of the three dimensional terrain mesh [3, 4] used for traverse planning [5, 6]. The first type includes navigation cameras (Navcams). The Navcams are black-and-white cameras that use visible light to capture panoramic, three-dimensional imagery. There are two pairs of Navcams on the rover. The second type of camera is the Hazard Avoidance Camera (Hazcam). The Hazcams are black-and-white cameras that use visible light to capture three-dimensional imagery. There are four pairs of Hazcams on the rover. High quality data, produced by both Hazcams and Navcams, is defined as data that is compressed at a rate of three to four bits per pixel [7].

The Curiosity rover body is connected to the six aluminum wheels by a “rocker-bogie” suspension system [8, 9], with three wheels on each side of the rover. Figure 1 illustrates the structure of this type of suspension. This suspension system is the same system found on both of the previous rover missions (Spirit and Opportunity). The wheels are individually milled out of aluminum blocks.

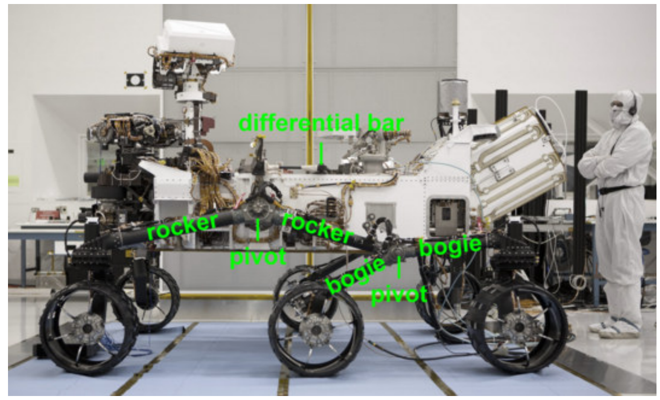


Figure 1. Rocker-bogle suspension on Curiosity [7].

The design and production of the wheels for the Curiosity rover was the same as the previous two rover missions, except for the grousers. Grousers, or treads, that protrude from the surface of each wheel are oriented in a chevron pattern on the MSL curiosity rover, as opposed to the straight line pattern utilized for the previous two rovers (Spirit and Opportunity). Figure 2 illustrates the design of the wheel, and the appearance of a grouser. The chevron pattern grousers are intended to prevent sideways slip of the rover.

Figure 2. Skin and grouser features on each of the six wheels [7].

Discovery of MSL Curiosity Wheel Damage

Approximately one year after landing on Mars, on sol 411, punctures were observed on both the left middle and left front wheels. After the conclusion of sol 491, a press release outlined the results of an imaging campaign that was established to investigate the extent of the wheel damage noticed in sol 411 [10]. The amount of wear appeared to have accelerated over the time observed [11].

In order to determine the reason for the accelerated damage, and how it could impact the rest of the mission, a Tiger Team was developed and deployed [9]. A Tiger Team is a group of interdisciplinary experts tasked with solving a very unique problem. This is the point where wheel damage or wheel wear became a significant event in the eyes of many in MSL operations [7, 12].

The Tiger Team determined that the wheel damage on the Curiosity rover is likely due to small, sharp rocks that are embedded in firm terrain, and smaller rocks that fit between the grousers. These rocks cause punctures in the aluminum skin of the rover wheel, when the rover travels over the rock [9]. Over time, the structural damage worsens due to increased stress, fatigue, and continued puncture events [9].

As a result of this wheel damage incident, four operational factors appeared. Operational factors are defined as the manifestations of changing decision making that affect day-to-day operations. In effect, these changes in operational policy represent an attempt by engineers to mitigate increased actual and perceived risk. The four operational factors that differed after the discovery of wheel damage include the distance traveled during a sol, the utilization frequency of autonav, the terrain risk weighting, and the high-level mission planning.

The remainder of this paper will discuss the methods that enabled researchers to capture the events and operations associated with this wheel damage event. The results section will outline the changes in operational factors that were observed by the researchers. A risk model will be introduced showing how specific factors changed contributions to human risk perception after the discovery of wheel damage. Finally, recommendations are made as to how the decision making in each of these scenarios could benefit from increased technology or changes in the training process.

2. METHODS

In order to understand the operational strategies that changed as a result of MSL wheel damage, we gathered data on operational strategies utilized over the lifetime of Curiosity. This included gathering data on operational strategies at the beginning on the MSL mission, strategies immediately following wheel damage, and present day strategies. These data were gathered utilizing three methods. The methods included interviews that occurred outside of the MSL sol planning environment, interviews and observation during MSL sol planning, and review of the "NASA Mars Rover Curiosity: Mission Updates" blog, provided by mission team members from USGS Astrogeology Science Center. Subsequent paragraphs will discuss each of the three methods in more detail.

The first method utilized consisted of a series of interviews *outside* of the MSL sol planning environments. The nature of each interview was semi-structured. Therefore, there was a framework of the themes that were investigated, but the interviewer was also open to exploring new avenues suggested by the interviewee. There was an array of different experts interviewed including surface property scientists, rover planners, and mobility test engineers.

The second method of data collection took place *during* sol planning for MSL operations. Data was collected by both observing the workflow that occurs during sol planning operations and by conducting semi-structured interviews with the personnel in the planning environment, during sol planning for the MSL curiosity rover. Individuals that were interviewed included surface property scientists and rover operators. Surface property scientists are experts associated with the Martian terrain. Rover operators are the individuals responsible for sending motion and trajectory commands to the rover.

The third method of data collection was to review the "NASA Mars Rover Curiosity: Mission Updates" blog, provided by mission team members from USGS Astrogeology Science Center. This blog, offering contributions from multiple members on the MSL Curiosity team, documents the events that occur for a large portion of sols on Mars. This blog acts as an archive where pertinent details are stored that help to elucidate key events that have occurred through the history of Curiosity. The blog was reviewed first for mentions of wheel damage or wheel wear. After finding those points in the blog, the blog was then reviewed for details concerning distance traveled by the rover, use of auto-navigation, operational procedures, and long-term trajectory strategies.

3. RESULTS AND DISCUSSION

Aggregating the results from the interviews, observations of operations, and archive/blog review resulted in the identification of four operational factors that changed as a result of the wheel damage incident. The analysis of these factors will then help to establish a Rover Risk Perception Model.

Rover Distance Traveled

The MSL Curiosity rover started at Bradbury landing in Gale Crater. The primary destination for MSL curiosity rover was the base of Mount Sharp. The approximate linear distance between those two points is 6.9 kilometers [7]. Due to the great distance between those two points, the Curiosity rover was designed with the capability to drive up to 200m during a given sol [1].

Rover distance traveled per sol is an operational factor that changed drastically since the discovery of wheel damage. The tendency to drive shorter distances was a risk mitigation strategy executed after the discovery of wheel damage. Samples of distances traveled before the discovery of wheel damage include 110m, 100m, and 141m (Average: 117m; Standard Deviation: 17.45m) [10]. Samples of distances traveled after the discovery of wheel damage include 60m, 70m, and 100m (Average: 76.67m; Standard Deviation: 16.99m) [10]. Interviews with rover planners confirmed that rover distance traveled was significantly shorter after the discovery of wheel damage [7, 12].

Utilization frequency of AutoNavigation (AutoNav)

Multiple pairs of Navcam (navigation camera) images provide stereoscopic images that are utilized in order to generate a terrain map of hazardous, rough, or rocky terrain. AutoNav is able to use this data in order to calculate a safe driving path in order to get to a designated endpoint. If the rover operators cannot view terrain before the uplink of a command sequence, then they cannot confirm if the terrain is, in fact, safe. Therefore, AutoNav can enable the rover to proceed safely into areas where rover operators have insufficient or no visibility by autonomously calculating a path [13]. AutoNav can also be utilized in order to plan trajectories on terrain that rover operators can view.

Utilization frequency of AutoNav is an operational factor that has changed significantly after the discovery of wheel damage. Before wheel damage, AutoNav was used frequently to add extra distance to the curiosity rover trajectory. After the discovery of wheel damage, AutoNav utilization has decreased drastically.

Terrain Risk Weighting

Curiosity was designed to operate on unforgiving Martian terrain. The rover, able to roll over obstacles 65 cm high and operate on steep grades of up to fifty degrees, was engineered to handle a multitude of obstacles [7]. The terrain risk weighting by a rover operator is an operational factor that changed drastically after the discovery of wheel damage. First, small, sharp rocks embedded in firm terrain are now avoided as much as possible.

The small rocks, which were not avoided in the past, now have an immense amount of risk associated with them because they were determined as the cause of small punctures in the aluminum wheels. Secondly, traditional obstacles Curiosity could handle previously (like obstacles greater than 65 cm) are avoided in order to minimize further damage to the punctured wheels [7, 12].

In order to reduce the rate of wheel damage, the MSL team decided that soft, loosely packed terrain was the terrain that offered the lowest amount of risk. The rover planners began prioritizing paths that included loose terrain over hard terrain in order to reduce the exposure of the wheels to obstacles that exacerbated wheel damage. However, this strategy proved to be troublesome when the MSL Curiosity rover experienced excessive slip in the soft, loosely packed terrain.

Changes in High-Level Mission Planning

In terms of mission planning at the supratactical level, changing a long-term trajectory so as to not exacerbate wheel damage is an operational factor that changed since the realization of wheel damage. Before the discovery of wheel damage, supratactical planning was executed in order to meet science-related goals. However, after the discovery of wheel damage, high-level planning was much more dependent on operational factors associated with the rover [5]. As a result, the science-related goals were lower in priority than the operational goals of moving the rover as safely as possible between waypoints.

The Rover Risk Perception Model

The identification of the four operational factors that changed as a results of the wheel damage incident led to the development of a Rover Risk Perception Model that captures those contributors to risk perception before (Figure 3a) and after the discovery of wheel damage (Figure 3b). These five contributors are control influence, long-term planning, mission risk observability, ground characteristics, and science objectives. The arrows connecting the contributors to risk perception in Figure 3a show that each of the five contributes some amount of notional risk to operators' overall perceived risk before the discovery of wheel damage. The similarities in arrow types indicate that the contributions were in equilibrium.

Figure 3b illustrates how human risk perception changed for each of these five contributors after the discovery of wheel damage. There are two key features concerning Figure 3b. One key feature is that the circle representing overall human risk perception is larger. This represents that human risk perception elevated after the discovery of wheel damage. The other key feature is that the contribution of risk from each of the five categories changed after the discovery of wheel damage. These changes are illustrated by changing the bolded arrows connecting the contributors to the human risk perception circle.

Four of the five contributors led to the increase in overall risk perception, as illustrated by Figure 3b, including long-term planning, mission risk observability, ground characteristics, and science objectives. The only element that contributed less risk to human risk perception after the discovery of wheel damage is the control influence factor. These will now be explored in greater detail.

Control Influence

The control influence factor represents risk related to the extent humans manipulate the rover. This includes how the rover traverses the terrain, and the proportion of the trajectory that the human plans (as opposed to automated planning). After the discovery of wheel damage, control influence over Curiosity increased, as an attempt by the operators to gain more control.

For example, the choice to not use AutoNav after the wheel damage incident for Curiosity motion planning can be explained by the control influence contributor in the Rover Risk Perception Model in Figure 3b. Instead of allowing the rover to utilize AutoNav, the operators elected to evaluate the terrain and choose the desired path without the aid of autonomy. This increase in control influence demonstrates how humans attempt to mitigate a risk perception increase by exerting more control, which may not always be the optimal course of action. As a result of this increased control influence, distance traveled by the rover decreased, as discussed earlier.

This level of increased control was an attempt by operators to lower their perception of risk (hence the dotted line in Figure 3b) but it is not known whether such actions lowered or increased actual risk. It is a common human risk mitigation strategy to exert more control in off-nominal operations for automated systems, but often doing so leads to more problems. Thus operators may take control to lower their perceived risk but sometimes in doing so, increase actual risk.

This type of behavior in another domain is exemplified by the fact that US Air Force pilots often prefer to land Unmanned Aerial Vehicles (UAVs) by hand, instead of relying on the auto-land feature. Our model suggests that operators reduce their perceived risk by increasing their control influence, thus insisting on manual landings as opposed to automatic ones. However, in reality, the manual landings have resulted in an *increased* number of accidents. This has led to so many accidents that the Air Force is now changing its operating procedures to mandate automatic landings [14]. This is an example that a human's risk perception does not always reflect the real risk.

Long-Term Mission Planning

The long-term planning contributor represents that portion of risk due to the planning of the rover, greater than one sol, with respect to the various science and rover objectives. The long-term planning process changed after the discovery of wheel damage. Before wheel damage, rover planning was predominately concerned with prioritizing science goals. However, after the discovery of wheel damage, priorities were shifted to reducing stress or damage to the rover. This resulted in a situation where progress towards science-related goals suffered due to the fear associated with damaging the rover. Due to this change in long-term planning, this contributor to human risk perception increased after the discovery of wheel damage.

Mission Risk Observability

The mission risk observability contributor relates to the ability of the operators to observe risk associated with the Martian area of operations. Given the remote nature of these operations, observability is directly related to those sensors and the onboard processing that gives operators information about the remote world.

The ability to observe risk associated with the mission has remained static for Curiosity. This is due to the fact that the sensory hardware has remained constant over the life of the mission. Because Curiosity is on Mars, operators are only able to observe the mission risk through existing sensory equipment. However, there is a desire for a greater amount of risk observability after the discovery of wheel damage. Therefore, this inability for information demands to be satisfied results in a greater risk contribution from mission risk observability to human risk perception.

Ground Characteristics

The ground characteristics contributor represents that portion of risk perception due to the various types of terrain that the rover has to traverse, such as sand and rocks. Depending on the characteristic of the ground, there could be varying risks associated with the features.

Overall human risk perception from the ground characteristics contributor increased after the discovery of wheel damage due to the increased terrain risk weighting. After the Tiger Team released their findings about the cause of the damage to the wheels, it was established that key ground characteristics posed a serious risk to Curiosity's wheels. Therefore, there was an increase in overall human risk perception from the ground characteristics contributor, which is the primary cause of the wheel damage.

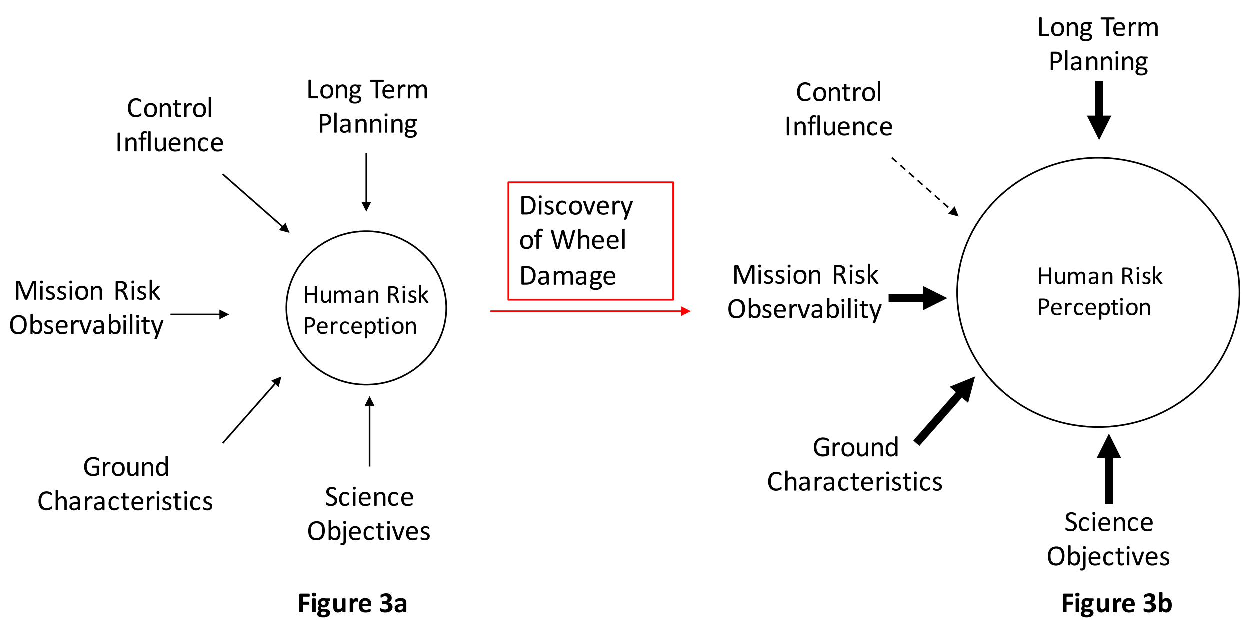


Figure 3. Evolving contributors of risk to human risk perception before (a) and after (b) the discovery of wheel damage

Science Objectives

The science objectives contributor encapsulates the risk associated with the failure to capture a sufficient amount of science data while on Mars. The inability to gather sufficient data could jeopardize the primary goal of MSL.

The science objectives contribution to human risk perception increased after the discovery of wheel damage. MSL went to Mars with the sole purpose of determining Martian habitability. There is a risk that MSL will be unable to collect enough data to answer the question of Martian habitability. However, after the discovery of wheel damage, that risk, both actual and perceived, increased.

Suggestions for Improved Decision Making

The Rover Risk Perception Model suggests opportunities where improvements could be made to improve decision making for the rover operators. There are two general suggestions, the first of which is developing a decision-support tool that utilizes a risk-aware autonomous planner. The second suggestion is to provide training that emphasizes appropriate levels of trust in autonomous systems and technology in cases of increasing perceived risk.

A risk-aware planner is a type of automated planning system that explicitly considers probabilistic events, such as the likelihood of the complete loss of mobility as a function of traverse distance, and computes a plan that limits the probability of undesirable events [15]. Such a risk-aware planner could be useful in assessing how much distance should be traveled, and the amount of weight to assign to the various terrain features. This planner would be able to quantitatively capture the risk associated with these features; also, the planner would not overweight risk due to the recency of an occurrence, etc. Therefore, the human could utilize a decision-support tool in order to reduce judgment errors associated with a biased or poor analysis of risk.

The second suggestion would be to provide training for the MSL planning team and rover operators that emphasizes appropriate levels of trust. Control influence has been utilized many times over the course of Curiosity's mission. Increased control influence shows that humans decrease their perceived risk by taking on more of the tasks completed by automation or autonomy. However, it is not clear what the cost is to overall mission goals to increase control influence.

In order to ensure that new technology is utilized, operators need to be more aware that exerting control influence has consequences on optimality, performance, and risk taking. This is crucial for the operational strategy where AutoNav has been utilized less frequently. It is important to draw the distinction between a lack of utilization due to autonomous system performance, or just an inappropriate level of trust in the autonomy.

4. Conclusion

Changes in risk perception often manifest in changing operational factors. These changes in operational factors often represent risk mitigation strategies. The ability to understand how risk perception changes due to a critical event is crucial for developing adaptive operational strategies and decision support technologies. This paper presents a Rover Risk Perception Model that explains the changes in operational factors and behaviors that occurred after the discovery of MSL curiosity rover wheel damage. The four specific operational strategies identified and investigated include the distance traveled by the rover during a sol, the utilization frequency of auto-navigation, the risk-weighting of varying types of terrain, and the changes in high-level mission planning.

Each of the four operational strategies was analyzed in the context of the Rover Risk Perception Model. This model, shown in Figure 3, helps to illustrate how contributions to risk perception increased or decreased after the discovery of wheel damage. There are two trends that were observed when comparing behavior before wheel damage versus after wheel damage. After the discovery of wheel damage, human operators exerted greater control influence over the rover. Also, science goals and objectives were deprioritized in favor of increased rover safety. The desire to exert a control influence over a system in a risky situation has been observed numerous time in varying scenarios [16].

Such changes in risk-weighting operational strategies as exemplified by the wheel damage incident demonstrate how technology and process improvements could help to anchor risk perception, and improve mission performance. A risk-aware planner could guide future Mars rover operations to have more consistent and objective risk perception and mitigation levels associated with the Martian terrain. Another suggestion for improved decision-making would be training for appropriate levels of trust in autonomous systems. This training could help operators understand the impact of changes in control influence, which could develop a more cooperative relationship between the autonomous system and the human.

Acknowledgements

We would like to thank the Office of Naval Research for funding this research initiative through contract #NNN12AA01C. We would also like to thank the Jet Propulsion Laboratory and members of the Mars Science Laboratory team. The research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1] Jet Propulsion Laboratory, "Mars Science Laboratory/Curosity Fact Sheet," ed.

[2] C. Debarati, A. Mishkin, A. Allbaugh, Z. Cox, S. Lee, G Tan-Wang, *et al.*, "The Mars Science Laboratory Supratactical Process," in *SpaceOps 2014 Conference*, ed: American Institute of Aeronautics and Astronautics, 2014.

[3] A. Mann. (2012, 08.07.2012) The Photo-Geek's Guide to Curiosity Rover's 17 Cameras. *Wired Magazine*. Available: https://www.wired.com/2012/08/curiosity-mars-rover-cameras/

[4] Jet Propulsion Laboratory. *Eyes and Other Senses*. Available:http://mars.nasa.gov/msl/mission/rover/eyesandother/

[5] M. Bajracharya, M. Maimone, and D. Helmick, "Autonomy for Mars Rovers: Past, Present, and Future," *IEEE Computer,* vol. 41, pp. 44-50, 2008.

[6] J. Biesiadecki and M. Maimone, "The Mars Exploration Rover Surface Mobility Flight Software: Driving Ambition," presented at the IEEE Aerospace Conference, Big Sky, Montana, 2006.

[7] M. Operators, "MSL Operators In MSL Planning Environment," M. Tucker, Ed., ed, 2016.

[8] Jet Propulsion Laboratory. *Wheels and Legs*. Available: http://mars.nasa.gov/msl/mission/rover/wheelslegs/

[9] E. Lakdawalla, "Curosity wheel damage: The problem and solutions," vol. 2016, ed. The Planetary Society, 2014.

[10] U. A. S. Center, in *NASA Mars Rover Curosity: Mission Updates*, ed.

[11] T. S. Group. (2014, 09.02.2014) Curosity Wheel Issues and Solutions: A Conversation with JPL's Jim Erickson. *Space Safety Magazine*

[12] M. Operators, "MSL Operators Outside Planning Environment," M. Tucker, Ed., ed, 2016.

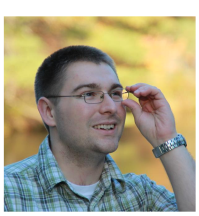
[13] G. Webster, "NASA's Mars Curosity Debuts Autonomous Navigation," ed. Jet Propulsion Laboratory, 2013.

[14] J. Paur. (2009) Can Killer Drones Land On Carriers Like Human Top Gun? *Wired*.

[15] M. Ono, B. Williams, and L. Blackmore, "Probabilistic Planning for Continuous Dynamic Systems under Bounded Risk," *Journal of Artificial Intelligence Research* vol. 46, pp. 511-577, 2013.

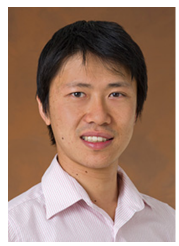
[16] N. Carr. (2013) All Can Be Lost: The Risk of Putting Our Knowledge in the Hands of Machines *The Atlantic*

BIOGRAPHY



Alexander Stimpson *received his B.S. degree in biological engineering from the University of Florida, Gainesville, FL, USA, in 2007, and the S.M. degree in Aeronautics and Astronautics from the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, in 2011. His dissertation work focused on the application of machine learning models to inform training assessment and intervention. His current research interests include human supervisory control, decision support systems, artificial intelligence, and data mining. He is currently a postdoctoral researcher for the Humans and Autonomy Laboratory at Duke University.*

Matthew Tucker *received his B.S and M.S degrees in Biochemistry from North Carolina State University in 2013 and 2015, respectively. Matt is a member of the Humans and Autonomy Lab at Duke University. He is specifically interested in developing a human-machine interface capable of conveying algorithmic perceptions of risk to human operators, but also capable of enabling human operators to convey human perceptions of risk to automation*



Masahiro Ono *received his B.S. degree in Aeronautics and Astronautics from the University of Tokyo in 2005 and a Ph.D. and S.M. degrees in Aeronautics as well as an S.M. degree in Technology and Policy from the Massachusetts Institute of Technology in 2012. He is a Research technologist in the Robotic Controls and Estimation Group. He is particularly interested in risk-sensitive planning/control that enables unmanned probes to reliably operate in highly uncertain environment. His technical expertise includes optimization, path planning, robust and optimal control, state estimation, and automated planning and scheduling. Before joining JPL in 2013, he was an assistant professor at Keio University.*

Amanda Steffy *is a Mission Operations Engineer in the Flight Systems Engineering Group. Amanda extensively addressed the MSL wheel damage as a member of the MSL Wheel Wear Tiger Team, conducted a terrain analysis tailored toward the wheel wear issue, and tested wheel life on the Mars-weight mobility vehicle. She currently works on the MSL Engineering Operations Team as a Mobility Chair and Systems Engineer assessing the health and performance of MSL. She earned her B.S. degree in Biomedical Engineering from Cornell University, and is currently working towards her M.S. in Aerospace Engineering at UCLA.*

Mary Cummings *received her Ph.D. in Systems Engineering from the University of Virginia in 2004. She is currently an associate professor in the Duke University Department of Mechanical Engineering and Materials Science, the Duke Institute of Brain Sciences, and the Duke Electrical and Computer Engineering Department. She is the director of the Duke Humans and Autonomy Laboratory.*