A Virtue Ethics Analysis of the Mars Climate Orbiter Failure

STS Research Paper
Presented to the Faculty of the
School of Engineering and Applied Science
University of Virginia

By

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March 1, 2020

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Problem Frame Introduction

The Mars Climate Orbiter was a National Aeronautics and Space Administration (NASA) robotic space probe launched in 1998. Built by Lockheed Martin Astronautics and operated by NASA Jet Propulsion Laboratory, the orbiter was intended to study the Martian atmosphere and climate. However, due to an error in a software file that erroneously used Imperial units instead of metric, upon Mars orbital insertion the spacecraft was lost due to navigational inaccuracies (National Space Science Data Coordinated Archive, 2000). The failure of the Mars Climate Orbiter received significant media attention, with headlines such as "Mars Probe Lost due to Simple Math Error" (Hotz, 1999) and "Metric mishap caused loss of NASA orbiter" (Lloyd, 1999). It is frequently mentioned in science and engineering classrooms as a warning for students to pay careful attention to units.

Due to the root cause of the failure being technically very straightforward, analysis of the incident generally focuses on how the management decisions and systems engineering strategies contributed to an environment where such a simple error was not identified and fixed. However, this approach overlooks the moral dimensions of the actions of the MCO navigation engineering team and the MCO navigation operations team. If the morality of the actions of the engineering and operations teams are ignored, then students lose the chance to learn about how an engineer should act ethically in technically complex engineering situations.

I will demonstrate that the navigation engineering and operations teams were immoral due their actions not meeting the standards of professional conduct for engineers. Specifically, I will use virtue ethics to evaluate how the team members lacked the following virtues for morally responsible engineers: Striving for quality, professionalism, and communication .

Background

The Mars Climate Orbiter was part of NASA's Mars Surveyor Program, a set of programs intended to meet planetary science objectives with smaller, less costly, and more frequent missions (referred to as faster, better, cheaper). The spacecraft was built by Lockheed Martin Astronautics (LMA), with additional contracted responsibilities to lead system integration and testing, as well as support launch operations. NASA Jet Propulsion Laboratory (JPL) was responsible for project management, mission design, and mission operations (National, 2000). After the spacecraft failed to correctly complete its Mars orbital insertion and communication was lost, the failure was traced to a single software file. Developed by LMA, the file was supposed to output the calculated force on the spacecraft during a type of navigational maneuver. The software specifications given to LMA by JPL stated that the forces should be output in metric, but instead the file used U.S. Standard units. Over the course of the spacecraft's journey to Mars significant error was introduced into the spacecraft's trajectory, which the JPL operations team failed to notice (Oberg, 1999). Nine months after launch, the orbiter's insertion into mars orbit failed and it either burned up in Mars' atmosphere or re-entered heliocentric space. The total cost of the mission was 193.1 million U.S. dollars.

Literature Review

A significant amount of research exists analysing the failure of the Mars Climate Orbiter. While the root cause of the failure is often used in engineering and science classrooms as an example of the importance of paying attention to units, analyses of the contributing factors generally focus on the project's program management in the context of NASA's "Faster, Better Cheaper" policy. Introduced by the then-current Administrator of NASA Dan Goldin in the

1990s, the policy spawned several highly successful small scale missions, but soon came under scrutiny with the high profile failure of several missions, including the Mars Climate Orbiter ("NASA reexamines Faster, Better, Cheaper", 2000).

Cordova and Gonzalez critically analyze the "Faster, Better, Cheaper" (FBC) policy, which involved changes at NASA to increase the robustness, flexibility, and efficiency of their scientific programs, in their 2017 *Mission to Mars Case Study*. Using two models of organizational theory, they investigate how the policy contributed to mission failures such as the Mars Climate Orbiter. First, they utilize the Diamond Model, a model to understand "the structure of the programmes, and identify the gaps between the current capabilities and what is required to make the programme succeed" (Cordova and Gonzalez, 2017, p 67). Using this model, they determined that FBC had gaps in all four Diamond areas: Novelty, Technology, Complexity, and Pace. The FBC missions generally involved new technology, with significant technical difficulties. However, the limited budget and increased pace of the FBC programs meant that significant innovation was often traded out for trial and error solutions. Additionally, the missions were generally very complex, but lacked a sufficient budget to provide a suitable development schedule and management of the complexities. Lastly, the FBC policy reduced the average development time of a mission from six to three and a half years. This accelerated timeline likely led to avoidable errors not being caught (Cordova and Gonzalez, 2017).

In Sauser, Reilly, and Shenhar's comparative analysis of the Mars Climate Orbiter loss, contingency theory is used to analyze how the failure was ultimately caused by managerial mistakes, not technical mistakes (Sauser et al., 2007). While the MCO borrowed a significant portion of its technology from previous missions, the connection architecture was still new.

Small changes in design created new interactions between components, and management failed to recognize gaps in systems level knowledge. Additionally, FBC had no clear guidelines or policies on how exactly the projects should become faster, better, and cheaper. This led to attempts to reckless strategies to decrease cost with one project manager stating “it was mandatory that we cut corners...It was mandatory that we didn’t get a second set of eyes on everything we needed to. Otherwise we could never have met the cost goals” (Sauser et al., 2007, p 673). They conclude that the management should have allotted more time to identify necessary architectural innovation, and the necessary resources to manage and properly vet architectural changes.

Although both these analyses offer valuable insight on how management and policy choices affected the Mars Climate Orbiter failure, they do not address the ethics of the actions of the engineers involved in the project. For engineering students, there is value in determining how the actions of the LMA engineering team and JPL operations team showed a failure to display the moral virtues of responsible engineers.

Conceptual Framework

My analysis of the morality of the navigation engineering and operations teams draws on virtue ethics, which allows me to determine what virtues are necessary for morally responsible engineering. Virtue ethics was first developed by Aristotle, who believed that the goal of human action should be to strive for the highest good. The good life, or “eudaimonia”, is a life in agreement with the virtues necessary to realize one’s human potential. Today, virtue ethics is recognized as a theory that focuses on the nature of an acting person, at what characteristics they have in order to be moral. Like utilitarianism and Kantian theory, virtue ethics involves criteria concerning actions, but instead of judging the morality of the actions it focuses on the traits of the actor and whether those traits are virtuous. As such, developing good character traits, called virtues, will lead to moral actions (van de Poel & Royakkers, 2011).

This leads to the question of what virtues an engineer should possess in order to be morally responsible. Many professional engineering codes of conduct make references to virtues an engineer needs. Michael Pritchard has developed a list of virtues for engineers (van de Poel & Royakkers, 2011, p 99): Expertise/professionalism, clear and informative communication, cooperation, willingness to make compromises, objectivity, being open to criticism, stamina, creativity, striving for quality, having an eye for detail, and being in the habit of reporting on your work carefully. A lack of any of these characteristics leads to poor engineering practice. For this paper, I will use the NASA Mars Climate Orbiter Mishap Investigation Report, supplemented with the Institute of Electrical and Electronics Engineers' (IEEE) analysis, to determine whether the actions of the navigation engineering and operations teams displayed the presence of the following engineering virtues: Striving for quality, professionalism, and communication.

Analysis

Before the morality of the actions of the engineering and operations teams are assessed, it is first necessary to understand the division of labor in the mission. The spacecraft was built by Lockheed Martin Astronautics (LMA). When discussing the navigations engineering team, I am referring to the group of LMA engineers who designed the guidance, navigation, and control architecture of the spacecraft, which includes software. NASA's Jet Propulsion Laboratory was responsible for mission management and operations. When discussing the navigation operations team, I am referring to the group of JPL engineers who became responsible for the spacecraft's trajectory being correct immediately after launch (Oberg, 1999). When discussing management decisions, it is the JPL Mars Climate Orbiter management team that is being referred to. Using virtue ethics, I will analyze how the navigation engineering team lacked the virtues of striving for quality, how the navigation operations team lacked professionalism, and how both teams failed to communicate and cooperate properly.

Striving for Quality

In order to understand how the LMA engineering team lacked the engineering virtues of properly reporting work and striving for quality, it is first necessary to understand the piece of software that contained the conversion error. During the journey to Mars, it was necessary to perform a maneuver called "Angular Momentum Desaturation" to remove angular momentum that would build up in the spacecraft's reaction wheels. During such a maneuver, the spacecraft's thrusters would be fired. Information on the thruster firing parameter was then passed to the ground software file "SM_FORCES", or small forces, which calculated the resulting force on the spacecraft from the thruster firings. The output from this file was then processed by other navigation software. The incorrect units caused the navigation software to underestimate the effect of an angular momentum desaturation event on the spacecraft's trajectory by a factor of 4.45 (Oberg, 1999). Although the forces involved were "small", over the course of the nine month mission errors in the trajectory accumulated, ultimately causing the mars orbit insertion point to be off by nearly 200 kilometers.

The presence of this error indicates that the LMA navigation engineering team lacked the engineering virtue of striving for quality. According to the accident investigation report, "the output from the SM_FORCES application code as required by a MSOP Project Software Interface Specification (SIS) was to be in metric units" (Mars Climate Orbiter Mishap Investigation Board, 1999, p. 16). It was clearly the responsibility of the navigation engineering team to ensure that all software met the specifications. Furthermore, the software engineering code of ethics states that "Ensure that specifications for software on which they work have been well documented, satisfy the users' requirements and have the appropriate approval" (Gotterban et al., 1997). The accident report states that "End-to-end testing to validate the small forces ground software performance and its applicability to the specification did not appear to be accomplished. It was not clear that the ground software independent verification and validation was accomplished for MCO. The interface control process and the verification of specific ground system interfaces was not completed or was completed with insufficient rigor" (MCO Board, 1999, p. 16). The navigation engineering team failed to meet the very low standard of using the units specified by their customer. If there had been rigorous "control" and "verification", it is impossible that such a mistake could have occured. Thus the engineering teams' actions show that they completely failed to strive for quality, thus lacking a basic engineering virtue.

Professionalism

The virtue that the JPL navigation team failed to display is professionalism. The Oxford English Dictionary describes a professional as someone "that has or displays the skill, knowledge, experience, standards, or expertise" necessary for an occupation (Oxford English Dictionary, n.d.). For the purpose of this analysis, we will focus on professionalism requiring skills, knowledge, and standards to analyze the ethics of the navigation operations team. First, the events during the operations phase which culminated in the spacecraft's loss are described, and then the operations teams' absence of the virtue of professionalism is discussed.

Angular Momentum Desaturation events began occurring after the launch of the spacecraft, which immediately began the introduction of small errors into the trajectory. Several months after launch, discrepancies were observed between navigation solutions, with observed doppler shift signatures not matching those of the navigational models. Despite being observed, these discrepancies were never resolved by the operations team. After the last planned trajectory correction maneuver, it became clear that the spacecraft was not where it should have been. There was a back-up plan in place to perform an extra trajectory maneuver, called TCM-5, but "the criticality to perform TCM-5 was not fully understood by the spacecraft operations or operations navigation personnel" (MCO Board, 1999, p. 19). until it was too late.

The Accident Investigation report explicitly identifies the operations teams' lack of knowledge of the spacecrafts characteristics as a cause of the failure, stating that "the operations navigation team was not intimately familiar with the attitude operations of the spacecraft, especially with regard to the MCO attitude control system and related subsystem parameters" (MCO Board, 1999, p. 18). There are several contributing factors to the operations teams' lack of knowledge. The operations navigation team came onboard shortly before the launch of the spacecraft, so they did not participate in any of the testing of the ground software. Additionally, they did not participate in the Preliminary Design Review (PDR) nor in the Critical Design Review (CDR) process (MCO Board, 1999, p. 19). PDR and CDR are part of the design review process, and contain all the information about the design. If the operations team had participated in the design process, even if it was just the guidance, navigation, and control portions, then they would have been much more knowledgeable of the spacecraft's systems. It is evident from the events described that the operations teams actions show a lack of the knowledge necessary to do their job, the skills required to deal with unexpected occurrences, and the standards of quality necessary to realize that something was very wrong.

Some might object to the characterization of the operations navigation team as unprofessional when it could be argued that management decisions are what originally caused the team to lack knowledge of the spacecraft. This is supported by the the accident investigation report discussing that "the lack of an adequate systems engineering function contributed to the lack of understanding on the part of the navigation team" (MCO Board, 1999, p. 21) and that project management did "not provide for a careful handover from the development project to the very busy operations project" (MCO Board, 1999, p. 27). However, I believe that once the operations team noticed discrepancies in the trajectory and were unable to determine the cause, it became their responsibility to educate themselves on the system. The operations team were obviously all aware of the fact that they had not participated in the PDR, CDR, or commissioning phase. Upon encountering something they did not understand, they should have immediately educated themselves on the spacecraft to fix their knowledge gaps. A more thorough understanding of the attitude control system would have helped them to identify the error.

Communication

The last virtue, that both the engineering and operations team lacked, is that of communication. Effectively communicating is an essential skill in any engineering project, especially one with a large number of participants and a very complex system. Although the accident board found that there was a lack of communication across many project sections, stating "In the MCO project [...] there is evidence of inadequate communications between the project elements, including the development and operations teams, the operations navigation and operations teams, the project management and technical teams, and the project and technical line management" (MCO Board, 1999, p 22), this analysis will again just focus on the engineering navigation teams and operations navigation teams.

An example of the engineering teams actions showing a lack of the engineering virtue of communication can be found in the number of the angular momentum desaturation events that occurred. Due to the MCO's asymmetrical solar array relative to the spacecraft body, it was believed that a daily 180 degree flip would be needed to cancel sun induced angular momentum build up. However, a guidance, navigation, and control, systems engineering study later determined that this was not actually necessary. However, the engineering team never communicated this fact to the operations team, which led to the angular momentum desaturation events being performed 10-14 times more than was necessary (Oberg, 1999). The engineering team's failure to communicate properly with the operations team greatly increased the effect of their original units error. There is no reason why the results of such a study should not have been shared with the operations team, which shows a clear lack of the virtue of communication.

The operations team also lacked the necessary engineering virtue of communication. Although they were aware of issues with the trajectory, as discussed in the previous section, the mishap report details that "it was clear that the operations navigation team did not communicate their trajectory concerns effectively to the spacecraft operations team or project management" (MCO Board, 1999, p 22). Once the operations navigation team realized something was wrong, it was their responsibility to escalate the concern to the management so more decisive actions or a thorough investigation could be started. No details are provided in the report about why the investigation board considered the attempts of the navigation team to communicate their concerns to have been ineffective. However, their judgement will be considered valid and the navigation operations team can be shown to have lacked the virtue of communication.

Conclusion

The morality of the Mars Climate Orbiter's navigations engineering team and navigation operations team can be evaluated using virtue ethics. I conclude that since the teams lacked the virtues necessary for responsible engineers, then their actions were unethical. Specifically, the engineering team lacked the virtue of striving for quality, and the operations team lacked the virtue of professionalism. Both teams failed to display the virtue of communication. Using virtue ethics, the actions of these engineers were evaluated and it was determined that they were immoral due to failing to possess the virtues needed for ethical engineering.

While the Mars Climate Orbiter failure is often mentioned to students as a stunning reminder to treat units cautiously, it perhaps has more value in its demonstration that lacking the virtues for morally responsible engineers can cause the simplest mistake to have disastrous consequences. Mistakes like using the incorrect units are likely common in the engineering process, but cultivating the proper engineering virtues makes it much less likely that they will cause the total failure of a project.

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