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Weaving Failure Analysis into a First-Year Robotics Project

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Weaving Failure Analysis into a First-Year Robotics Project

Background and Rationale

This complete evidence-based practice paper describes the evolution and subsequent assessment of what began as a failure analysis component in an existing first-year engineering cornerstone course. The Ohio State University's First-year Engineering Honors program engages students in an intensive design-and-build robotics project in the second course of a two-course sequence [1]. The primary educational goal is to give students a realistic engineering experience, leading to educated decisions about whether engineering is the profession they want for themselves, and, if so, which engineering discipline to pursue as a major. The real-world engineering elements include teamwork, budgeting, project planning, oral and written communication, documenting, microcontroller programming, prototype construction, and electrical wiring. All of these experiences are incorporated within the overall design, testing, and refining of the robot.

This course has been offered for over two decades and continues to evolve. It has always included required performance tests at relatively regular intervals. These are to help keep the teams progressing on a reasonable schedule, but also to help them determine whether their product is performing as intended. Instructor observations revealed that many teams were approaching the performance tests primarily as local endpoints and were not taking advantage of their formative nature. Instead of discussions of long-term solutions, teams were focusing on the short-term achievement of passing a particular performance test. To combat this tendency, in 2017, a failure analysis component was added to the course [2].

Inspection of the literature indicates that this was a relatively unique approach. Most articles that discuss failure analysis in engineering education come from particular engineering disciplines, such as civil engineering or materials science, and describe approaches such as providing parts that previously failed to students to analyze [3] or including case studies of prior events in the discipline [4]. A recent publication [5] describes an approach in a third-year aerospace engineering course where students were presented with a group design task that was set up to be unsolvable (without the students knowing this). When progress stagnated, the students were led through a series of reflective exercises culminating in individual failure reports. The approach described in the current paper differs from those in previous publications in that 1) it was assigned to first-year students, 2) it was infused into an ongoing design-and-build project, 3) students reflected on their own recent failures, and 4) students were expected to ultimately be successful in achieving the design goals of the project.

In the first iteration of the exercise, any team that received fifty percent or less on a performance test was required to engage in a failure analysis. They were to identify the causes for why the robot did not achieve the goals of the test, along with likely strategies for remedying the problems identified. Additional details of the initial assignment and how it fit into the course context are described in an earlier publication [2]; a summary of the assessment found in that paper is provided below, as it sets the context for this study.

The first time this assignment was incorporated in the curriculum, there were four performance tests, and about half of the participating teams engaged in one or more failure analyses. Coding of the student responses, focusing on the causes of failure and the proposed solutions for mitigating it, showed that while students were able to describe a variety of possible causes for the failures, their analyses were lacking in suggestions of how to address the shortcomings or failures. Additionally, a non-negligible number of teams proposed solutions that did not align with any of the problems they described. Further, a question on the end-of-course evaluation indicated that while many students found value in the assignment, many also missed the point of the exercise [2]. However, it was the opinion of the instructors that the reflective aspect of the analysis was valuable and that all teams would benefit from engaging in the process. Indeed, one of Chickering and Gamson's seven principals for good teaching practice is giving students the opportunity to reflect in a way that provides prompt feedback [6].

In a more recent offering of the course, the assignment was revised so that all teams were required to submit a reflection following each performance test, regardless of its outcome. The new version of the assignment also included more scaffolding to connect identified problems to proposed solutions, asking students specifically how they would address each problem they had described. Additionally, it asked students to identify strengths of the design, not just the weaknesses, as it is equally important to have students reflect on what they know, rather than just what they do not know [6]. Further, the iterative nature of engineering was highlighted, as the assignment explicitly prompted them to think about future performance tests, their final product, and the next time the robot would need to perform the tasks from the test they had just completed.

Context and Details of the Revised Assignment

The revised assignment was included in the spring 2019 offering of the course. The tasks the robots needed to perform were presented through the scenario of assisting at an arcade. These included starting when a light in the floor was illuminated, pushing one of two buttons, inserting a lost token in a slot, sliding some foosball counters, flipping a lever, and signaling the end of a run by pushing a large button. There were four performance tests during the semester that collectively included each of the tasks required of the robots. Each week also included a "stretch bonus" task to encourage teams to think about how the tasks for that week would connect with subsequent performance tests. More details on the performance test structure and how it fits into the course have been provided previously [2]. About a week after the fourth performance test, teams had three attempts at a complete run; this day is referred to as the individual competition, and teams were also required to complete the reflection assignment following it.

The new version of the assignment begins with the following introduction:

> One of the hallmarks of engineering design is reflecting on performance to determine which elements of the design are working as intended, which are not, and what opportunities exist for improvement in future iterations. Therefore, following each

performance test and following the individual competition, each team must prepare and submit a short reflection, either in the form of a ½- to 1-page paper or in a brief video.

This is followed by a set of questions to be addressed in the submission, asking about whether the design met the specifications, whether it performed as expected, what the strengths and weaknesses of the design were, what elements should remain the same going forward, and how the design could be improved the next time the same or similar tasks needed to be performed. Then teams are asked to identify problems that were experienced during the test, along with the causes of those problems, and to describe how they will address each of the problems to ensure future success. The full post-performance test reflection assignment has been provided as an appendix. To help contextualize examples in the text that follows, an overview of the performance tests from 2019 is provided in Figure 1.

Performance Test 1 – Claw Lever
Required: Robot must navigate to the claw lever and flip it down.
Stretch bonus: Return to the lower level

Performance Test 2 – Dance Dance Robot (DDR)
Required: Robot must navigate to the DDR area, read a light, and hold the correct button.
Stretch bonus: Navigate to the upper level and touch the foosball counters

Performance Test 3 – Token Deposit
Required: Robot must navigate to the upper-level token deposit and place the token in the slot.
Stretch bonus: Flip the claw lever

Performance Test 4 – Foosball Scoring
Required: Robot must navigate to the foosball area, slide the scoring counters all the way to the left, and press the final button.
Stretch bonus: Press any button on the DDR

Figure 1. Overview of performance tests

Data and Analysis

All the reflections for seven teams in one section of the course were qualitatively coded. Each team submitted five reflections (one for each of the four performance tests, plus one for the individual competition.) This resulted in 35 reflections to code. A phenomenological interpretivist perspective was used, since the data and conclusions drawn from them are the products of the environment in which the students and instructors were working [7,8]. The qualitative coding was combined with a semi-quantitative analysis to describe trends in the content of the student submissions. The analysis was conducted to answer the following questions:

1) Did the revised assignment result in teams suggesting more solutions for problems they identified? How explicitly were solutions linked to problems?
2) Were the kinds of problems identified and solutions proposed similar to those given by students in the previous study?
3) Did the revised assignment succeed in getting teams to more explicitly discuss plans for their robot's future success?

In short, the analysis indicated that the revisions to the assignment did impact the content of the reflections in a positive way. First, unlike the previous version of the assignment, where teams wrote significantly about problems they encountered, but provided relatively few solutions (and sometimes did not provide much connection between the problems and solutions), this time the teams described more solutions than problems. Teams identified a total of 87 problems and 107 solutions. In some cases, teams suggested multiple actions to solve a problem; in other cases, they went beyond the specific issues that arose in a performance test to describe additional work that would improve their robot. For instance, during the first performance test, one team found that their navigation method, which relied entirely on shaft encoding, worked well enough to get them through the test, but was not as consistent as it would need to be. They then shared a well-reasoned plan to gradually introduce new features to their software until they achieved the desired robustness, re-evaluating the navigation's reliability after each addition to determine when they had reached the goal.

Of the problems presented in the reflections, 90% were followed by a solution directly linked to them. Additionally, almost all of the solutions included specific actions to be taken; only two reflections had a vague statement of "more testing" as a solution. This is vastly different behavior than what was seen in the earlier analysis, where the teams discussed nearly twice as many problems as solutions, and there were often no explicit links in a given reflection between the two [2].

A second major finding was that there were shifts in the general categories the problems and solutions presented by the teams fell into. In the previous assessment, time management was the leading category for problems and mentioned by half of the teams as part of a solution. With the new assignment, time management was essentially "in the noise," only being mentioned a total of four times as a problem factor and only once as part of a solution. The problems reported by teams overwhelmingly fell into three categories: hardware (43% of problems reported), navigation (29%), and software (13%). Hardware problems were things like mechanisms falling off of servos, wheels or axles becoming loose, or center of gravity issues. Examples of software issues included getting stuck in infinite loops, having incorrect values in the code, or needing to make the code's logic more robust. Sometimes navigation issues were reported generically and sometimes teams would describe a particular difficulty, like not being able to reliably reach a particular point on the course. The most common categories for solutions were hardware (38%) and software (36%). Note that typically a navigation problem is solved using some combination of software and hardware modifications. None of the other solution categories (i.e., testing more effectively, changing actions taken by the team during performance tests, adapting course strategy, improving time management, making sure the controller was optimally charged, or making substantial overall design changes) accounted for more than 7% of the presented solutions.

The final question of whether the explicit wording encouraging forward thinking in the students was effective or not also has a positive answer. In 47, or 44%, of the solutions provided, teams included wording specifically linking their solutions to improved robot performance in the future. Further, these comments accounted for nearly all of the solutions that were not directly tied to one of the identified problems. For example, one team wrote after the third performance test, "The group also decided that, while it was only introduced into our code this week and was only used very [*sic*] in a very small part of the movement, RPS [a particular navigational tool that is available] will be used much more in the following weeks because it was extremely effective in confirming the position of the robot and we believe that it will greatly improve the capabilities of the robot in navigating the full course." As another example, one team that achieved a perfect score on the first performance test wrote that "the official test was successful in part due to luck…. The design…has the capability to perform well, but mechanical concerns with the drivetrain warrant the complete redesign of the drivetrain, as the current support of the axels [*sic*] will not be sufficient for the final design." It should be noted that this team did invest the time in a substantial reworking of their drivetrain and that their robot achieved multiple perfect runs in the final competition.

There were also places where students described their awareness of how an adjustment to deal with a problem that arose in preparing for the most recent performance test would have implications (sometimes positive, sometimes negative) for future development and testing of the robot. One team wrote in their first performance test reflection about how they had raised the mount of an arm on their robot so it could apply enough torque to flip the lever on the course. While they were pleased with the way they had solved the problem in time to do well on the performance test, they identified two ways in which this design modification impacted their future strategy. In particular, they realized that they would need to reshape the gripping mechanism on the end of the arm so that it would still be able to slide the foosball counters when coming at them from a slightly different angle. This realization was particularly farsighted considering that the performance test involving the foosball counters was over a month away.

Discussion and Future Directions

This analysis indicates that the modest modifications made to the assignment were effective. A failure analysis was converted to a post-performance test reflection. As part of this reworking of the assignment, a few more specific prompts were added to guide the thoughts of the students to 1) specifically propose solutions to problems they had identified and 2) think about how information from the current test could impact the robot's future performance. The reflections that resulted showed the influence of these prompts, with students making clear connections between the problems their robots were experiencing and the solutions they were considering. They also described how their planned actions based on the information from the tests would influence the future performance of their robot. Prior to introducing these exercises to the course, robot deficiencies that were obvious to the instructional staff but that had not adversely impacted the score on a performance test often went unacknowledged and unaddressed by the teams, leading to reliability problems. Encouraging the students to articulate these issues appears to have been much more impactful than the instructors or teaching assistants warning the students about what might happen in the future.

One limitation of this analysis is that it only considered teams in one section of the course and may not be a representative sample, as many of the robots from this section performed very strongly at the final competition. In the future, we would like to repeat this analysis with more teams to see whether the trends identified here are generally applicable.

References

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Appendix - Complete Wording of the [Revised] Post-Performance Test Reflection Assignment

Post-Performance Test Reflection:

One of the hallmarks of engineering design is reflecting on performance to determine which elements of the design are working as intended, which are not, and what opportunities exist for improvement in future iterations. Therefore, following each performance test and following the individual competition, each team must prepare and submit a short reflection, either in the form of a ½- to 1-page paper or in a brief video.

Items to address in your paper or video:

- How well did your design meet the specifications of the performance test?
- Did your design perform as you expected it to? (Note that this is a different question from the first one!)
- What are the strengths of the design? What elements should remain the same going into the next performance test or competition?
- How can the design reasonably be improved for the next time your robot needs to perform these tasks?
- What problems did your robot experience, and what were the causes of these problems?

    - Was it a hardware problem?
    - Was it a software problem?
    - Was the team not ready (i.e. behind schedule, not enough testing, team efficiency, etc.) for the performance test?
    - Was the problem with the design or the execution? For example, you're pleased with the design but some aspect of the design did not perform as you expected, or you think the design created the problem but the execution was fine.
- How will you address each of the problems to ensure success in the future?

Requirements:

- Paper
    - ½ to 1 page in length
    - Single-spaced
    - Reasonable font (e.g., Times New Roman, 12 pt) and margins

OR

- Video
    - 2-3 minutes in length