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# BYOE: A Laboratory Experiment with a Stirling Engine for Troubleshooting Education in Mechanical Engineering

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## Abstract

Troubleshooting is a systematic approach to problem solving that involves identifying the root cause of a problem and finding a solution to address it. Strong troubleshooting skills requires not only a combination of technical knowledge and critical thinking skills, but also strong communication skills to collaborate with others to efficiently solve complex problems. For instance, team must find a faulty component in a malfunctioning machine by using a systems approach, and then develop a solution to make it functional. Whether it is a technician performing routine maintenance on an engine, an engineer trying to solve technical problems on a production line, or a medical doctor trying to diagnose a disease given symptoms, troubleshooting is an essential, transferrable life skill that can be applied to nearly any complex problem in any discipline or industry. While troubleshooting is a sought-after skill in engineering industry and academia, traditional mechanical engineering curricula does not have formal instruction for developing troubleshooting skills.

In this “Bring Your Own Experiment” (BYOE) work, we present an experimental Stirling Engine setup and introduce different and multiple flaws into the system to teach troubleshooting to undergraduate mechanical engineering students. The experimental setup consists of a two-cylinder Stirling engine, a heat source, and a propeller that is used to mix a fluid. The engine uses the thermal energy at the hot end to produce mechanical work at the impeller shaft output.

We use a resistance wire with variable input electric current to adjust the energy input to the machine. To alter the torque output of the engine, we change the fluid viscosity at the propeller end. Sensors are employed in the experimental setup to measure the operating conditions of the machine. A thermometer measures the temperature of the hot cylinder. An in-house built tachometer quantifies the rotational speed of the impeller shaft.

We offer students a troubleshooting exercise in an engineering experimentation course at a mid-sized technological university. Students are given a scenario in the troubleshooting exercise. According to the scenario, the Stirling engine is used to mix a fluid at a given speed. We create a sub-standard output by using a higher viscosity liquid at the impeller end and as well as by decreasing the input energy. Students identify symptoms of the sub-standard system, formulate hypotheses for causes, identify faulty components, devise solutions, and validate their solutions. In this work, we describe the experimental setup and the engineering knowledge that relates to the system. Students' performance on troubleshooting is presented subsequently. Average time to resolve troubleshooting errors, sample student hypotheses and how they relate to engineering knowledge are given in this work.

## 1. Introduction

The lack of strong troubleshooting skills is a common problem in engineering and non-engineering disciplines. Whether it is a technician solving a complex refrigeration problem in a supermarket, or an electrical engineer troubleshooting an op-amp circuit, or an ombudsman trying to troubleshoot errors in an organizational scheme, or a medical doctor diagnose a disease, troubleshooting is a common skill that is desirable within many disciplines. Troubleshooting is a cognitive task that deals with a system in a faulty state and produces operations on the malfunctioning system until a desired performance level is achieved [1]. Troubleshooters engage in a search for a faulty component until all possible error sources are exhausted [2]. This is followed by a component-level replacement or repair that removes the faulty state.

### *1.1. Structured Troubleshooting*

Troubleshooting problems are too diverse to be taught on a case-by-case basis. A systematic approach that is general to all troubleshooting problems is crucial. We present the troubleshooting model developed by Schaafstal *et al.* in this work. These authors analyzed naval weapon service technicians troubleshooting performance using cognitive task analysis to improve naval engineering service training [3,4]. Their work resulted in a framework that consisted of three elements: (1) tasks to achieve troubleshooting, (2) required knowledge and skills; (3) novice to expert transition (memory effect). Tasks in this framework are cognitive and general to all troubleshooting problems. Knowledge and skills of the framework are problem dependent but can be generalized into categories such as domain, device, process, experiential, and procedural knowledge. Novice to expert transition involves interesting phenomena associating human memory and cause generation in troubleshooting [5].

Troubleshooting is a recursive process in which tasks are executed in a non-linear fashion. Troubleshooting starts with formulating problem description, which requires an ability to make a distinction between standard and sub-standard performance of a system. Once a sub-standard response is identified, possible causes of the failure are sought through forming hypotheses. Each hypothesis needs to be tested and verified to see whether it is a cause for the failure. If possible causes are rejected, new possibilities are generated and tested. Final cause(s) are formed out of a space of possibilities. To complete troubleshooting, corrective action is taken to eliminate the cause(s) by either repairing or replacing relevant physical components. These tasks are shown using a flowchart in Figure 1. Similar recursive models with functionally identical tasks were introduced in other studies and manuals [6].

While troubleshooting is a sought-after skill in industry, traditional mechanical engineering curriculum does not provide training for troubleshooting. In this Bring Your Own Experiment (BYOE) study, we present a low-cost and portable physical model to train Mechanical Engineering students for troubleshooting. We present the construction details of the physical setup, the errors we implanted in the physical setup to create a troubleshooting problem, student response to the problem, and as well as, future work to advance instruction of troubleshooting.

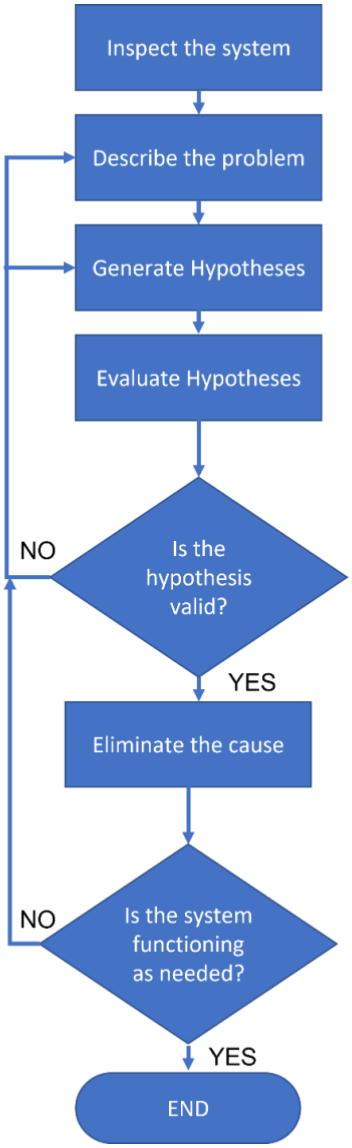

**Figure 1.** The process and tasks in structured troubleshooting

## 2. Materials and Methods

The BYOE setup was used to train students for troubleshooting skills in a junior-level engineering experimentation course at a mid-sized technological university. This course had an enrollment of 59 students that are Mechanical, Aerospace, and Robotics Engineering majors. The course is a lab-intensive course where students attend 4-hour laboratory sessions and 2-hour lectures per week. The course was run over a 7-week term. The troubleshooting exercise was given to the students in a laboratory session that was 2 hours long. Students worked in a team of 2 students to complete the exercise.

### *2.1.Fabrication of the Setup*

Students were given a Stirling engine setup that was malfunctional. The setup is shown in Figure 1a. The physical model uses a *gamma-type* Stirling engine, which is commercially available for under $60. We used 3-D printer parts, commercially available shafts, miter gears, and *in-house* machined parts to build an impeller system to agitate fluids. The impeller is immersed in a liquid and mixes the liquid as the displacer cylinder end is heated. Heating is achieved by Joule heating a shape memory alloy (Nitinol) wound around the displacer piston. For each Stirling engine seven and half windings of the resistance wire are built. The shape memory alloy retained its shape once it was wound on the cylinder and heated to 500 $^{o}$C. A DC power supply was used to provide 50W of power to heat the wire. Heat resistant cement was to hold the wires in place during heating (Figure 1b). Once the wire cooled down, it retained its shape. Using a resistance wire for heating eliminated the potentially hazardous open flame. The pulley system and the miter gears are used to transfer mechanical power to a vertical shaft that bears an impeller at its end. Impeller was immersed in a liquid, and when the machine was in motion, the impeller agitated the liquid. The bill of materials is given in Table I.

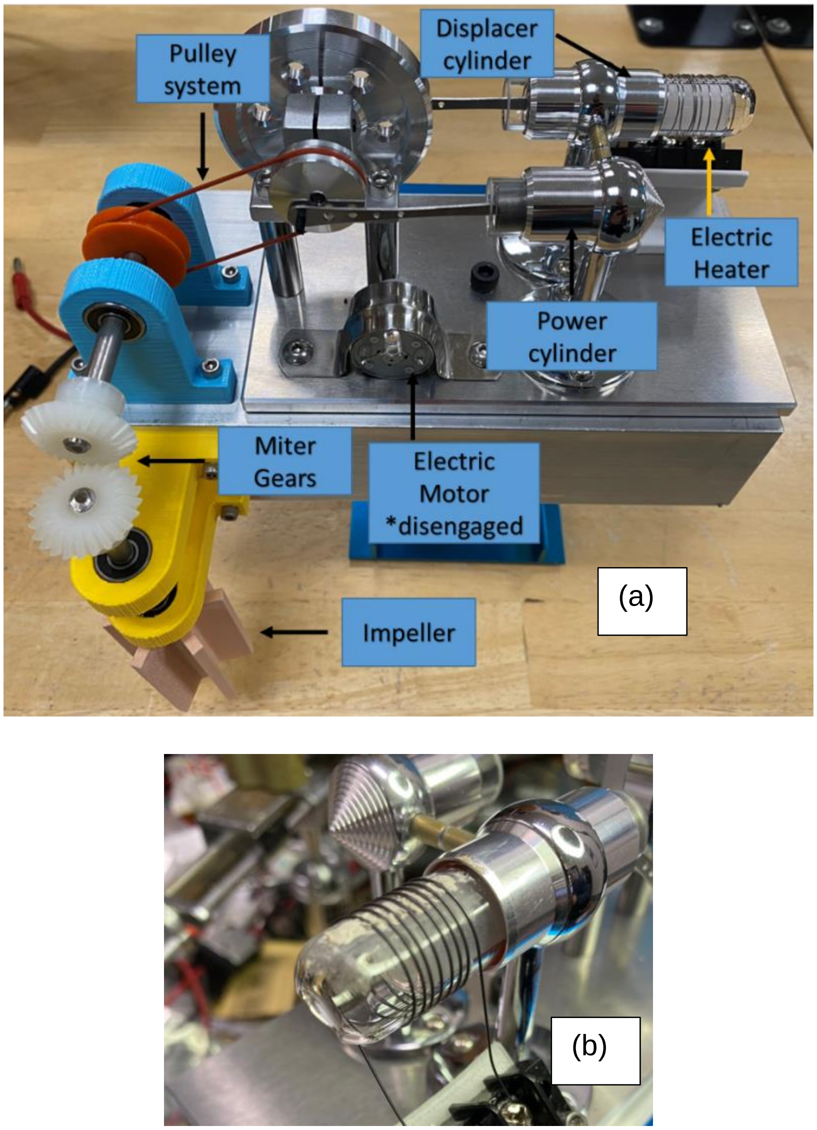

**Figure 2.** The troubleshooting setup used in the study (a). A commercially available gamma-type Stirling engine is modified for this study's purpose. In this setup, an electric heater provides the heat energy to run the impeller. The load on the impeller is determined by the viscosity of the liquid that it stirs. Close view of the heating coils on the displacer cylinder (b).

**Table I.** The Bill of Materials for a Stirling Engine Setup

| Vendor | Part # | Item | Price | Quantity |
|---|---|---|---|---|
| Amazon | N/A | Stirling Engine | $59.99 | 1 |
| Amazon | N/A | Base Adjustable Lab Jack | $19.99 | 1 |
| Amazon | N/A | Ball bearings for ¼” shaft | $12.99 | 4 |
| Amazon | N/A | Shape Memory Alloy Wire | $9.99 | 1 |
| Amazon | N/A | DC Power Supply | $59.99 | 1 |
| Mc Master-Carr | 8982K58 | L shaped aluminum (each l=8.5") l=8ft | $125.99 | 1 |
| Mc Master-Carr | 8934K26 | Stainless Steel rod for shaft d=1/4" | $41.97 | 1 |
| Mc Master-Carr | 7297K15 | Plastic Miter gear 24 Pitch | $8.87 | 2 |
| Mc Master-Carr | 91732A707 | Helical 6-32 inserts length 0.276" | $8.25 | 1 |
| Mc Master-Carr | 71732A450 | Helical installation Tools | $47.38 | 1 |
| All Electronics | TS-203 | Electrical Barrier Block | $1.30 | 1 |
| All Electronics | 22RD-100S | 22 GA. Red Hook up wire Solid 100' | $9.95 | 1 |
| All Electronics | 22BK-100S | 22 GA. Black Hook up wire Solid 100' | $9.95 | 1 |
| All Electronics | 22YL-100S | 22 GA Yellow Hook up wire Solid100' | $9.95 | 1 |
| 3D Printed | N/A | Rubber band pulley for 1/4 " shaft | -- | 2 |
| 3D Printed | N/A | Mounting for 1/4" bearings | -- | 4 |
| 3D Printed | N/A | Propeller for 1/4" shaft | -- | 1 |
| 3D Printed | N/A | Electrical Barrier Block Holder | -- | 1 |

### *2.2.Gamma Stirling Engine*

Gamma type Stirling engines are a type of external combustion engine that use a closed cycle to convert thermal energy into mechanical work. It operates on a regenerative thermodynamic cycle [7]. It typically consists of two cylinders: one hot and one cold, which are connected by a regenerator. Regeneration, or the regenerative cycle, is a process in which heat is transferred from the hot side of a Stirling engine to the cold side through a porous material allowing for more efficient energy transfer and improved engine performance. The working fluid, hydrogen, is alternately heated and cooled as it passes between the two cylinders, driving a piston and generating power. The two power pistons, one located in the hot cylinder and the other in the cold cylinder, are connected to a common crankshaft and operate 90 degrees out of phase with each other [8]. The hydrogen within the engine is contained in a working space that is shared by both cylinders, and it is circulated between the hot and cold cylinders by a regenerator.

During operation, the engine works in four stages:

1. Compression: The gas is compressed in the cold cylinder, which causes it to heat up and increase pressure.
2. Heating: The gas is then transferred to the hot cylinder, where it expands isothermally and produces work by moving the power piston.
3. Expansion: The gas is then transferred back to the cold cylinder, where it expands isothermally and produces more work by moving the other power piston.
4. Cooling: The cycle is completed as the gas is returned to the hot cylinder and undergoes adiabatic compression, which cools the gas and prepares it for the next cycle.

The operational principle behind gamma type Stirling engines is based on the Stirling thermodynamic cycle, which uses a fixed amount of gas to repeatedly undergo isothermal expansion and compression, as well as adiabatic expansion and compression, in order to produce useful work.

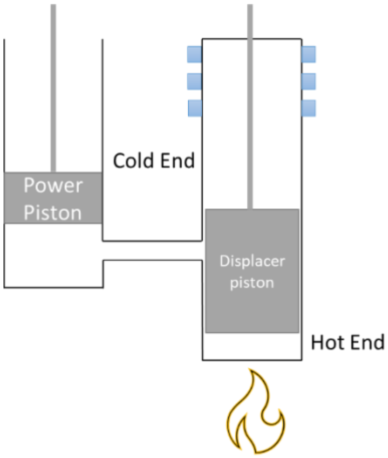

**Figure 3.** A schematic of a gamma-type Stirling engine. Displacer and power piston are in 90 degrees phase difference in gamma-type engines. The displacer piston displaces the high-pressure gas to the power piston that in return creates a power output.

In order to have a setup for every two students, we utilized around 80 person hours of effort to produce 20 copies of this setup (Figure 3). The instructional team also examined the efficiency of these setups using the input power at each setup and the corresponding output power at the impeller. Impeller power, $Pout$ can be calculated using the formula:

$$Pout = N_p * \rho * n^3 * d^5 * K$$

where, $Np = 1.5$ is the power number for the impeller geometry, $\rho = 1{,}000$ is density of the fluid (water) in $kg/m^2$, $d = 0.035$ is diameter of the impeller in $m$, and $K$ is the corresponding Reynold's number for each station setup. Table II shows the setup efficiency at five measured stations.

**Table II.** Efficiency calculations for the setup. The speed is measured as the impeller is running in water.

| Station # | Voltage (V) | Current (A) | Input Power $P_{IN}$ (W) | Speed (RPM) | Speed (rad/s) | Impeller Power $Pout$ (W) | Efficiency |
|---|---|---|---|---|---|---|---|
| 1 | 12.8 | 4.93 | 63.10 | 156 | 16.33 | 6.86 | 10.87% |
| 2 | 12.8 | 4.96 | 63.49 | 163 | 17.06 | 13.14 | 20.70% |
| 3 | 12.8 | 4.96 | 63.49 | 163 | 17.06 | 11.53 | 18.17% |
| 4 | 7 | 3.65 | 25.55 | 157 | 16.43 | 13.90 | 54.39% |
| 5 | 8.2 | 3.48 | 28.55 | 192 | 20.10 | 15.74 | 55.14% |

The instructional team placed each setup on students' workstations and immersed the impeller in glycerin. In the problem statement given to the students, students needed to mix the glycerin using the Stirling engine; however, the setup had errors preventing the machine to work. The instructional team implanted the following two errors in the setup.

- The electric potential applied to heating wires was insufficient to generate output motion.
- Miter gears were in proximity but not meshed or rubber band was not engaged to the pulley, such that no mechanical power could be transferred to the vertical shaft.

The students were given the following excerpt at the beginning of the exercise.

“Please find a Stirling engine setup on your desk. An electrical heater provides heat energy to the system and this energy is used to stir fluid using an impeller. You will find the impeller stationary and the setup not in motion.

Your goal is to identify and solve problems in the setup so that the impeller is in motion in a fluid. You will work with a partner for this exercise. Only one submission per team is needed. You are welcome to ask for new parts/components, fluids, etc. but the instructional team will not give you any hint on solving the problems. You will work with your lab partner to deliver this assignment. One submission per team. But please do not get help from others. You are welcome to use any source that you want (online, book, or lecture notes) but please don't communicate with other groups in the lab.

You have one full hour to complete this lab. If you finish early, you can leave or work on your missing labs.”


(a)

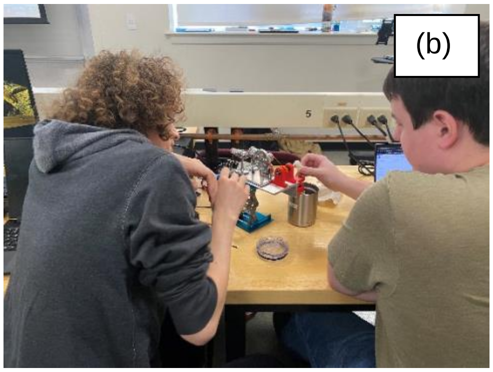
(b)

**Figure 4.** A commercially available gamma-type Stirling engine is broken apart and re-assembled to include an impeller at its end. We produced 20 copies of this system to serve 40 students at a time (a). A team of two students troubleshot the error that we have implanted in the setup (b).

The learning objectives of the exercise are as follows.

- Ability to plan and execute strategies to solve troubleshooting problems.
- Ability to work with a partner in a structured problem-solving activity.
- Ability to use engineering domain and device knowledge in practical problem-solving scenarios.

## 3. Results and Discussion

The structured troubleshooting presented in the Introduction section involves identification, hypothesis generation/verification, and solution tasks. Hypotheses present a spectrum of possible errors causing the malfunction. Hypotheses need to be tested and verified to find the true cause of malfunction. Students were exposed to a 50-minute lecture on troubleshooting prior to the laboratory exercise. The instructor used the troubleshooting framework developed by Schaafstal *et al.* in structuring the lecture [3,4]. Briefly, the framework consists of (1) identification of the error through observation of symptoms, (2) finding the probable causes of the error, (3) solution of the error. To our observations in the laboratory, students are competent in identifying the problem, whereas they require substantial help in identifying the causes of the error. Solution of the error sometimes requires replacement of the faulty component, and according to our observations, students do not struggle with the solution step. In order to help students with the troublesome component of troubleshooting – identification of error causes, the instructor promoted effectual logic over causal logic. We hypothesize that effectual logic could help students prepare relevant hypotheses for the cause of errors. Briefly, effectual logic refers to producing means given present resources that is in contract to causal logic, which uses a given mean [9]. Students completed two exercises in the classroom to practice effectual logic. In the first, students are asked to list all possible types of meals that could be cooked using a given set of ingredients. Second, instructor showed students a picture of an electro-mechanical setup that is shown in Figure 5. In the imaginary scenario, the button in this setup was not functional. In response to this given error, students were asked to list all possible causes of errors, essentially learning how to populate hypotheses. We instructed students to follow the troubleshooting framework and effectual logic when they are given the troubleshooting problem. In addition to the problem solving skill development in the lecture, students were given a brief introduction to Stirling engines.

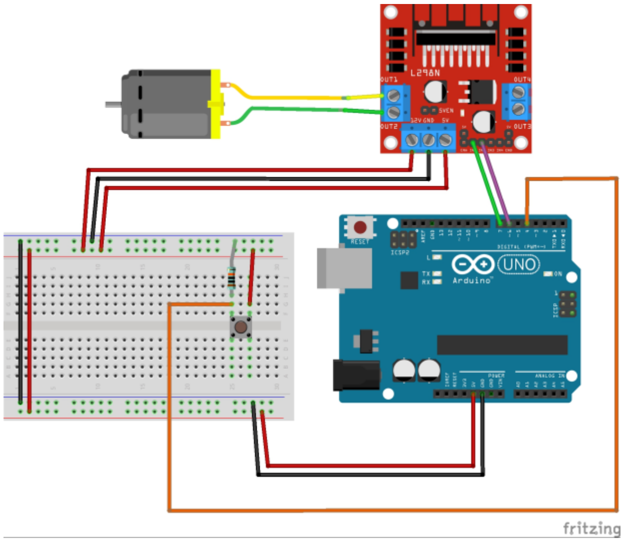

**Figure 5.** A troubleshooting scenario that is used to instruct students on hypothesis generation. According to the scenario, a push button is used to reverse the direction motor spin. The button is not working as intended and students find probable causes to this error. Students have previously completed this exercise in the lab.

In the laboratory, students generated hypotheses, tested them using measurement tools in the laboratory or simply by observation, and devised solutions for validated hypotheses. Students used a worksheet to organize their work towards troubleshooting. The worksheet is a table that contains a list of hypotheses, their validations, and respective solutions at the end of the exercise. A sample table is given in Table III. In the table, the rows represent different components in the Stirling engine setup, and the columns indicate possible problems, their identification, and solutions. A sample student worksheet is given in Appendix A.

**Table III.** A Sample Student Worksheet for Troubleshooting Activity

| **Generated Hypothesis** | **Hypothesis Testing** | **Solution** |
|---|---|---|
| Mechanical transmission failure at the gears. | It is visually apparent that the gears are not in contact. | Successfully joined the gears together. |
| Impeller is not connected to the shaft. | We can confirm that the impeller is connected to the shaft by visual observation. This hypothesis is rejected. | N/A |
| Heat input to the heat engine is not sufficient to create an output motion. | Measure voltage and current at the resistance wires at the displacement cylinder. | Adjust voltage level until there is the desired output. |

We report data from 21 student teams from a single offering of this troubleshooting exercise. All student teams were able to finish the exercise under two hours. The median time to finish the troubleshooting experiment was 62 minutes. The median number of hypotheses was 4. Figure 6 presents the degree of association between the time to complete the exercise and the number of hypotheses generated within this time frame. We report no correlation between these two quantities, although our initial thought was that the time and the number of hypotheses would be proportional. According to our observations, a relatively small amount of time was spent for hypotheses generation and testing, as students first spent a relatively large amount of time understanding the device, its components, and their relationship.

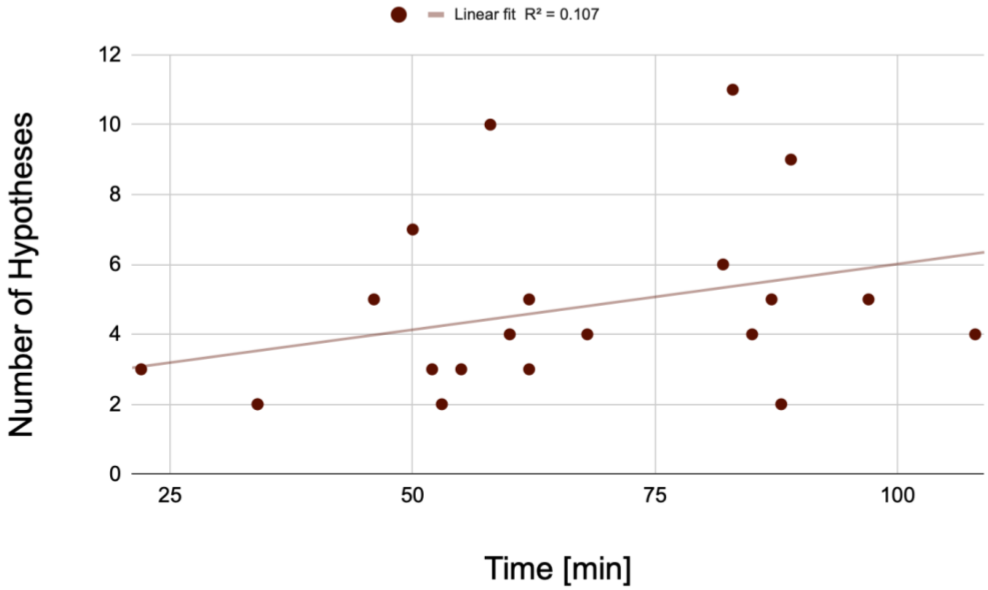

**Figure 6.** The plot of time spent to solve troubleshooting problem against the number of hypotheses generated in this timeframe.

There are known solutions to the troubleshooting problem that we presented to students. Increasing the heating power solves and meshing the gears or pulley with rubber band solve the troubleshooting problem. In addition to this, the setup provided students other possible ways to initiate motion in the system. The DC motor in Figure 2a has a pulley on its shaft. This pulley was not connected to the impeller shaft by a rubber band initially. If the electric motor is connected to the impeller shaft pulley using another rubber band, such that both DC motor and

Stirling system energizes the impeller in tandem, one can set the system into motion without changing the input voltage. In addition, the problem statement given in the preceding section states that in the working condition, the Stirling engine would agitate a fluid. Fluid type is not specified. The impeller was initially immersed in a relatively high viscosity fluid, glycerin, causing a higher torque output. Changing the fluid to water also sets the system to motion without changing the input power to the engine. Another solution to set the engine to motion was to decrease the temperature of the cold end of the displacer cylinder as heat engines run on the temperature difference between hot and cold ends. A student achieved cooling by wrapping moist towel around the cold end of the cylinders. In the exercise, 90% of the teams utilized at least one of these alternative solution for the troubleshooting problem. These modes of repair created unexpected opportunities for students and diversified the solution space.

## 4. Conclusions and Future Work

This is a pilot study to verify the design of a troubleshooting exercise for mechanical engineering undergraduate students. We present our design in detail and show student work in a single offering of the exercise. We currently work on investigating type of flaws that could be potentially added to troubleshooting exercise. We ultimately want to understand students' approach to troubleshooting exercises and design interventions to make them better problem-solvers.

While this work is a preliminary study to report an initial laboratory verification of an BYOE experiment, we have some suggestions for future studies on engineering troubleshooting. First, students could be given a list of possible hypotheses to test. In this way, a standard way of measuring student performance could be achieved. In addition to this, some hypotheses could include erroneous information in terms of engineering knowledge, such that they could be used to measure understanding of the engineering material. Therefore, student performance not only in problem solving but also their competency in the application of engineering concepts could be measured. Our future work will include measurements for the use of engineering domain knowledge and effectual logic in the troubleshooting exercise.

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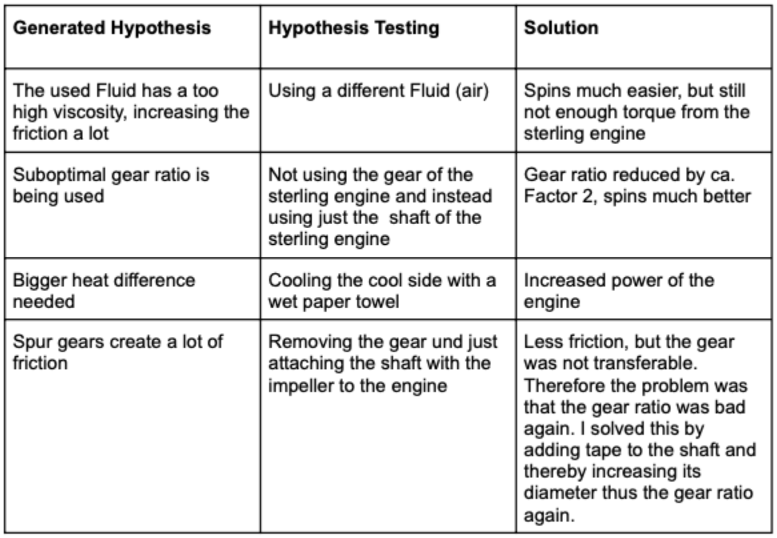
## Appendix A

Student artifact for the laboratory exercise. The work shows how student is engaged in finding solutions that are not standard solutions as deemed by the instructor.



| **Generated Hypothesis** | **Hypothesis Testing** | **Solution** |
|---|---|---|
| The used Fluid has a too high viscosity, increasing the friction a lot | Using a different Fluid (air) | Spins much easier, but still not enough torque from the sterling engine |
| Suboptimal gear ratio is being used | Not using the gear of the sterling engine and instead using just the shaft of the sterling engine | Gear ratio reduced by ca. Factor 2, spins much better |
| Bigger heat difference needed | Cooling the cool side with a wet paper towel | Increased power of the engine |
| Spur gears create a lot of friction | Removing the gear und just attaching the shaft with the impeller to the engine | Less friction, but the gear was not transferable. Therefore the problem was that the gear ratio was bad again. I solved this by adding tape to the shaft and thereby increasing its diameter thus the gear ratio again. |