Project 2 | Going the Distance

ME 104: Mechanical Systems Design

Overview:

In this project, you will work in a team to design, fabricate and test a simple robot, upload test data and video, and explain your design in a brief written report. Your robot will be designed to move up an I-beam as fast as possible while carrying an offset load. You will use a design process that blends intuition, concept generation, back-of-the-envelope analysis, computational analysis, models of motors and gears, design for mass efficiency, empirical testing, and technical writing, iteratively and with appropriate balance. Your team will fabricate the design using your personal 3D printers and the provided components. Grades will be based on objective performance, a summary report, and peer evaluations.

Learning Goals:

1. Design of mechanical systems involving electric motors and gears.
2. Mass-efficient design of assemblies with multiple custom and catalog components.
3. Applying the Design Approach to a complex problem in a team setting.

Materials:

We will provide you with a Tamiya 72001 gearmotor kit and some small shafts and bearings. We will provide an I-beam, an adjustable power supply and long lead wires in the d'Arbeloff atrium. Your team will have a box to store your robot and materials on the shelves in the d'Arbeloff Lab.

Specifications and Constraints:

Mechanical task: You will design a robot to climb up an I-beam as fast as possible while carrying an offset payload. The I-beam will have the length and orientation depicted in Figure 1, with cross-section as depicted in Figure 2. The payload will be made of aluminum, with dimensions as depicted in Figure 3. It must be carried with position and orientation relative to the I-beam as depicted in Figure 3 (note that this view looks along the centroid of the I-beam, not horizontal). It may not deviate from this relative position by more than 0.5 inch in any direction at any point during the climb. The robot and the payload must move in unison; the robot cannot remain stationary while the payload is lifted or vice versa (no winches), and no portion of the robot can remain stationary while the rest moves (no grappling hooks). Placing the robot on the I-beam must take less than 1 minute, including any fastening or assembly that occurs with the robot in place. Climbing speed will be defined by the time required for the robot to traverse 1 m along the length of the I-beam. Any 1 m section will suffice. Displacement can be measured using markings on the beam, and time should be measured using a stopwatch (app). During the climbing phase, nothing should touch either the robot or the payload other than the I-beam and the electrical leads. You will design your robot to minimize the time required for the robot to go the distance. That is, you're going for speed.

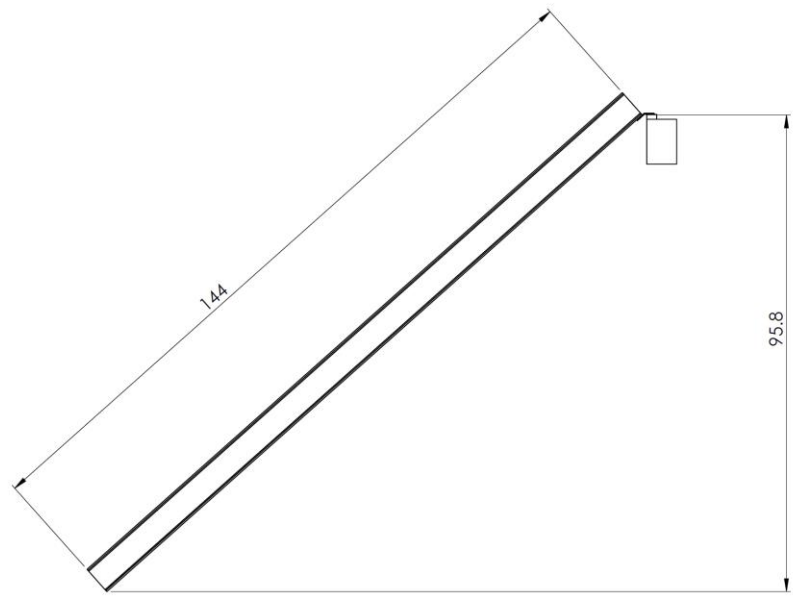

Figure 1. Side view of testing I-beam. Dimensions in inches.

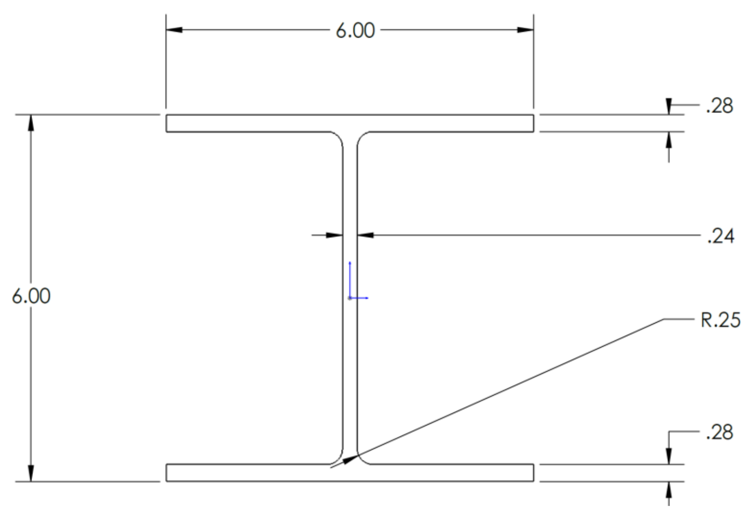

Figure 2. Cross-section of testing I-beam. Web is at center of flanges.

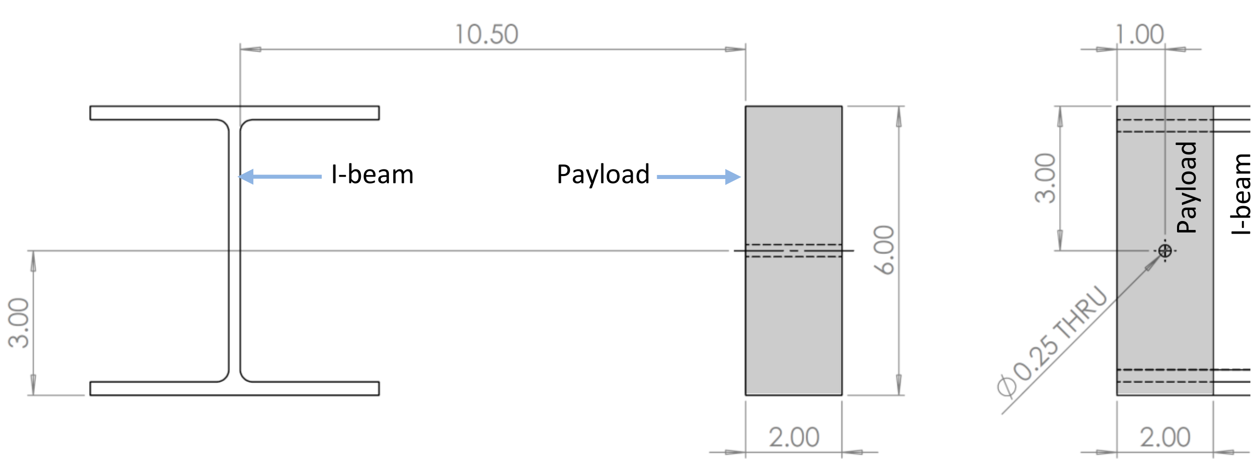

Figure 3. Payload location and dimensions. *Left:* axial view. *Right:* side view (cropped).

Robot components: Your robot will comprise custom components that you design and fabricate using your 3D printer, your choice of the provided shafts and bearings, the provided electric motor, and your choice of any portion of the provided planetary gearbox kit. You may only use PLA for custom components. You may connect custom components together using adhesives (hot glue, superglue, etc.) but you must ***not*** use any other materials for your robot (no popsicle sticks, rubber bands, purchased components, etc.). According to our tests, the dynamic coefficient of friction for 3D-printed PLA on lightly lubricated extruded aluminum is approximately 0.1. The ball bearings we have provided have a radial load rating of 500 N.

Motor: We will provide you with the Tamiya 72001 kit (www.pololu.com/product/70/), which includes the Mabuchi RC-260SA-2295 brushed DC electric motor (www.pololu.com/file/0J15/rc_260rasa.pdf). The motor characteristics listed here are inaccurate, and you will conduct experiments to identify the actual characteristics as an entry ticket. This motor must be the only source of mechanical power for your robot.

Motor thermal characteristics: We previously conducted experiments to identify the thermal characteristics and maximum allowable voltage for this motor. The thermal resistance, Rt, is about 31 K/W, the thermal capacitance, Ct, is about 29 J/K and the maximum allowable temperature is about 50 °C. The maximum voltage that can safely be applied is 6 V. Higher voltages can be applied for brief periods of time, but this is risky. To keep things safe and fair, we will treat this as a strict limit.

Warning: This motor can overheat easily! As we will learn, when a motor is stalled, or prevented from rotating, it experiences its highest current. The motor coil heats up in proportion to current squared. Above the maximum allowable temperature, the insulation on the coil wires will burn, shorting the coil, after which the motor will no longer work as well. Indications of a burned-out motor are lower torque output and higher current consumption. This motor should never be stalled for more than a few seconds at a time, and only at low voltages. For example, if we apply 6 V and accidentally stall the motor for 10 or 20 seconds, poof! The magic smoke will come out. It will overheat even faster if already warm, and it cools slowly, requiring up to an hour to return to ambient temperature. In a freezer, the return takes about 15 minutes.

Power supply: In the testing area outside d'Arbeloff are several adjustable power supplies with leads and alligator clips. To power your motor, attach the leads to the screw terminals at the base of the power supply, *set the desired voltage*, and, when ready, clip the other end to the motor leads. You can set the voltage to the desired value using the coarse and fine adjustment knobs. This supply can provide 30 V, but do not exceed 6 V for this project. For most use cases, you will want to set the current limit to the maximum by turning the coarse and fine knobs for current (not voltage) all the way clockwise. This will not dictate the current that will be applied, which will be an outcome of the applied voltage and speed of the motor, but it will prevent the current limit from interfering with your tests. When testing, you can use the power supply to measure the current using the display. The power supply may not switch off quickly when turned off, so the most reliable way to power down your motor is by removing the clips from its leads.

Gears: A planetary gearbox is provided as part of the Tamiya 72001 kit. You can select a gear ratio by building in more or fewer stages and by selecting the gear ratio at each stage. The orange stages are 5:1, the brown stages are 4:1, and there are two of each, making the maximum gear ratio 400:1. Before starting to assemble the kit, read the kit instructions carefully, read the tip sheet and watch the assembly video; there are some trickly little aspects, and some steps are hard to reverse. You may use anything in the kit, but must not use more than one box worth of components in your robot.

Gearbox loading: Note that, in addition to energy loss due to gear tooth meshing, the side load on the output shaft of the gearbox due to interactions between the robot and its environment will also create a friction torque that resists movement. It may be helpful to characterize this as well, and FBDs of the metal output shaft are useful here. It is best to connect the gearbox to your robot using the provided footers.

Warning: These gears can hurt you! This little motor and gearbox can produce a lot of torque and power. For example, stalled at 6 V with the maximum gear ratio of 400:1, this system can produce over 5 Nm of torque! Do not grab any part of the system while it's spinning; even just the gear on the motor output can Dremel off skin. Do not hold the gearbox output shaft with your fingers; the metal spring pin can tear skin. Always apply a torque to the system through a capstan or similar component.

Tamiya gear strength: We have performed tests to failure with the Tamiya planetary gearbox to help with your designs. The gears themselves are surprisingly strong, in part because there are three planets, each of which pushes both on the sun and the internal gear, such that the output torque is distributed across forces at six mesh points. The first thing to fail is actually the spring pin on the output shaft; this will shear or buckle out-of-plane at about 2 Nm output torque. If you substitute a stronger pin, the next feature to fail will be the sintered connection between the output shaft and the metal plate that interfaces with the final gear cage; this will shear at about 3 Nm of output torque.

Optional custom gears: If you wish to include custom gears in your robot, you may design them in CAD and fabricate them using your personal 3D printer. You are welcome to explore various ways of obtaining gear CAD models, including downloading them from McMaster-Carr. We have also provided a starter CAD file that you can modify to set the desired diametral pitch, number of teeth and face width. We are only able to provide an editable version in SolidWorks, so let us know if none of the members of your team has SolidWorks access and we can provide un-editable models with the desired gear profiles. Once you have the spur gear shape, you can edit any of these files to add other features, for example to connect the gear rigidly to other elements, connect it to a shaft using a press fit (which can be effective for transmitting radial loads but typically transmits only very small torsional loads), or provide other desired mechanical functions. In the provided starter CAD file, we have included a connection to the output shaft of the Tamiya gearbox using the same geometry as the capstan. You are ***<u>not</u>*** required to use custom gears.

Modifying the custom gear: Open ME104_Spur_Gear.SLDPRT in SolidWorks. Click Tools > Equations… In the window that pops up, find the rows for diametral pitch, number of teeth, and face width, then edit their values in the column labeled "Value / Equation". Click "OK", and the gear will update. You can set the number of teeth to between 5 and 60 (see Gears TR for some suggestions on how to choose). You can use more than 60, but will then need to go into the tooth sketch and make some little tweaks. After choosing the desired gear properties, you will likely want to add connection features specific to your system, and add some corresponding fillets and chamfers. When you save as STL, set the precision to the highest setting so that the involute tooth shape is preserved. When slicing in Cura, make sure there are sufficient print lines within the teeth to print well. After printing, you may need to clip away excess material, say from the first few layers or brim, to make sure the teeth will mesh well. You might include a little extra face width with this in mind. You can lubricate your custom gears with a silicone grease or (briefly) vegetable oil.

Some Design Tips:

- You can probably separately consider the tasks of (a) choosing the motor set point and overall gear ratio, from motor speed to robot speed, and (b) chassis design, at first.
- Free body diagrams are extremely useful for this project! It is worth doing them early and thinking deeply about what they mean. You will probably find it helpful to analyze the whole robot and payload (from all three views), each element in the transmission, and the motor + gearbox.
- Mass-efficient parts use less material and print faster.
- Press fitting and gluing can be good ways of connecting shafts and bearings to your custom components for radial loading (but generally not for torque transmission). To get the overlap just right for a press fit, it is helpful to print a small, simple test component, perhaps even with a few different hole sizes, to find just the right size for your printer.
- Superglue can be used for permanent, rigid assembly joints of 3D-printed PLA components. It helps to roughen the surfaces and to wait longer than usual for the glue to set.
- Hot glue works well for permanently joining PLA components. Just be careful not to over-melt the components and be prepared to work quickly as the glue cools rapidly.
- The Tamiya kit comes with machine screws, nuts and washers that you can use to connect the gearbox to your custom frame. If alignment is a concern, you can use oversized through-holes for these screws and tighten the motor in place once aligned.

Teams:

Some teaming tips: You and your teammates are inextricably linked! You must work together to succeed. Here are some tips based on the experiences of students in prior offerings of this course:

- Try to be productive, proactive, and positive in your comments and suggestions, always coming from a place of respect and looking for the best way forward. For example, rather than letting a teammate know what they’ve done wrong, suggest a way they could do something better.
- Communicate your status regularly, even if this sometimes means explaining that you haven't yet accomplished what you set out to do.
- Attend meetings and respond promptly to messages; everyone needs to stay on the same page.
- Take on your fair share of responsibilities for the project, remembering that your teammates are counting on you and will be evaluating your performance.
- Don't take on more than your fair share, remembering that your teammates are entitled to the experience of struggling with this project just as you are, and that you couldn't do everything yourself even if you tried.

- Try to allocate each type of work evenly, so that each team member has a hand in each part of the process: concept generation, back-of-the-envelope analysis, computational analysis, fabrication, prototype testing, writing, and figure preparation.

- There must be intellectual continuity throughout the project, which requires each team member to follow the design from concept, through detail, testing, and reporting. Besides, that's the fun way to do things :-).

Kick-off meeting: Your team will have a kick-off meeting in the first few days of the project in which you set goals, roles, meeting times, messaging platforms and a team name. The agenda must include:

- *Goals:* Do you want to, for example, try to win an award, maximize learning of a particular skill, or simply minimize effort to pass? You and your teammates will need to agree on goals. This will likely require some compromise from everyone, but you must all agree and then stick with it.

- *Roles:* Do you want to lead, for example, motor analysis, powertrain or chassis? Everyone should lead a substantial portion of each of: design, analysis, fabrication, and reporting.

- *Meeting times:* You will have some opportunities to meet up during some coaching sessions, but you will also want two or three separate times per week to meet independently from class.

- *Messaging:* Decide on a way to communicate asynchronously, be it Slack, Discord, Snap Chat, text thread, IM, landline, owl, walkie talkie, or 7” vinyl record, and get everyone set up.

- *Team name:* You need a team name so that your awesomeness can be properly recorded in Stanford’s educational annals. Clever names appreciated.

Outcomes and evaluation:

System testing: You will test your robot and record the results via an online survey, linked from Canvas. You will provide: the applied voltage; the total gear ratio, from motor rotational speed to robot translational speed; the measured motor current and climb time; a video of the robot being placed on the I-beam in less than 1 minute; a video of the final system test, which includes first a close-up of the robot and then a wide shot of the robot, payload, and power supply during the test. We recommend using YouTube and Google Drive to share linked videos, files, and photos. If using Drive, please set link access to “Stanford” so we can all check out your design.

Performance-based grading: A portion of the project grade is based on whether the robot was able to nominally complete aspects of the task, and on objective system performance. The performance-based grade will be calculated as

$$Performance\ Grade = 20\% \cdot Nom\ +\ 10\% \cdot \frac{1.2 \cdot (t_{slow} - t_{lift})}{(t_{slow} - t_{fast})}$$

where *Nom* is: 0.25 for a complete robot; 0.5 for a complete robot that sits on the I-beam with the payload; 0.75 for a robot that climbs at least 0.1 m with the payload; and 1 for a robot that completes the full climb in at most 10 minutes (to avoid a traffic jam). For the relative performance term, t_{lift} is the time your robot required to climb the distance, t_{slow} is a relatively slow climb time, and t_{fast} is a relatively fast climb time. To emulate real-world conditions, we won't set 'slow' or 'fast' values in advance; you will need to use your design and analysis skills to determine for yourself what you think is possible for this scenario. Please be assured that we will select reasonable values, and that if all designs are excellent then everyone will receive the top performance grade. Notice that designs with speeds near the fast value will receive a grade bonus.

Design Challenges: We will give awards for:

1. Fastest climb.
2. Manufacturing excellence – the best-built 'bot.
3. Best style – open to interpretation.
4. Best summary report.

Summary Report: Please submit a 12-page summary report explaining your design, submitted as a single PDF in response to the Canvas assignment. The report should be divided into the following sections:

1. **Photo Page:** Please include the following on a single page (10% of report grade)
   a. ***Names:*** The name of your team and names of team members.
   b. ***Robot Images:*** A few photographs of your robot, with all key features visible.

2. **Summary Page:** Please include the following on a single page (40% of report grade)
   a. ***Description and Reasoning:*** 500 words <u>or fewer</u> describing the design's primary features and why they are appropriate for this scenario. We're looking for <u>a very clear, convincing explanation for each major design decision, based on mechanical systems design concepts</u>. We expect <u>high-quality writing</u>, resulting from several rounds of editing.

3. **Free-Body Diagram Page:** Please include on a single page (10% of report grade)
   a. ***Byline:*** Name of the team member who led the creation of this section.
   b. ***Free-Body Diagrams:*** Provide a free-body diagram of the entire robot-payload system from each of three orthogonal views. Indicate only significant external forces and moments. Use vector notation to visually indicate their approximate magnitudes and directions.
   c. ***Force and moment values:*** List the estimated values for each external force and moment.
   d. ***Explanation of Assumptions:*** 100 words or fewer describing any assumptions you made to complete the free-body diagram analysis.

4. **Transmission Analysis:** Please include on three pages (20% of report grade)
   a. ***Byline:*** Name of the team member who led the creation of this section.
   b. ***Set-Point Approach:*** (one page) Please provide 300 words or fewer describing your process for choosing the applied voltage and motor-to-robot speed ratio. Feel free to refer to:
   c. ***Set-Point Diagrams:*** (one page) Please provide any equations and figures needed to understand your approach to selecting and achieving your desired motor set point.
   d. ***Power Flow:*** (one page) Please provide an accounting of where power from the power supply went during the climb, for example to Joule heating of the motor or friction heating of the gears. Include quantitative estimates for each power out term, in Watts.

5. **Component Analyses:** For the two most critical custom-designed, 3D-printed components, please include on three pages for each component (10% of the report grade each)

a. ***Bylines:*** Name of the team member who led creation of each component section.
b. ***Description and Reasoning:*** (one page) Please include a clear image of the custom component. In 300 words or fewer, explain each important feature and why it was chosen, using mechanical systems design concepts.
c. ***BOTEA:*** (one page) Please provide the most important aspects of the simplified analysis used to design the part. We expect free-body diagrams and inverse failure analysis.
d. ***FEA:*** (one page) Please provide the most important aspects of the computational analysis used to design the part. Include a brief explanation of the loading and constraints used.

Self and peer evaluation: You will complete a brief survey reporting contributions to the project and ease of collaboration for yourself and your teammates. This feedback will be provided to your team members to help them to appreciate the aspects of their teaming that went well and to provide suggestions for ways they could do better next time. A portion of your project grade will be based on both the quality of your comments to your teammates and your peers' perception of your contributions and collegiality.

Project Grade: The overall project grade will be calculated as:

$$Project\ Grade = Performance\ (30\%) + Report\ (60\%) + Peer\ Evaluations\ (10\%)$$