Applied Robot Design: How to Fix, Modify, and Build Robots

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Our proposed educational innovation is developing mechanical intuition in students through hands-on lectures and lab-based reinforcement and repetition of concepts.

The author Isaac Asimov established the three laws of robotics, the first, and most-important of which, states that, "A robot may not injure a human being or, through inaction, allow a human being to come to harm." Apparently no-one told the robots that this injury applies to a human's research productivity, too. In fact, the irony of robotics research is that much of a student's effort is spent fixing or modifying the robot's hardware rather than using it as enabling-infrastructure for new research. We aim to fix this.

Robotics is the nexus of engineering disciplines; it requires working knowledge of electronics, programming, mathematics, controls, and mechanical design. Research often requires that a student be able to perform at least basic tasks in all areas. While there are classes that teach the basics of most of these areas (e.g. EE122 for circuits, CS106B for C++, E105/205 for controls, and CS223A for robotic theory), no course exists to teach students how to design and build mechanical systems that would be used in a robot. The closest course is ME218, which is a 3-quarter series that covers electronics and software design for embedded systems. Although the students build simple systems with a few direct-drive motors, there is no instruction on the mechanical design, relying instead on *ad hoc* designs. Material presented to undergraduate mechanical engineers covers mostly theory, such as calculating bolt stress, rather than practical design. Students who need to perform even simple mechanical tasks often waste much time relying on others or teaching themselves. Robotics students learn quickly that robots are fragile and that fixing them on a monthly to yearly basis is part of life, even for expensive robots and careful students.

As one example, perhaps a student is testing a new computer vision algorithm that allows for a WAM arm to grasp objects more reliably. A week before the paper deadline, a software bug causes the arm to break itself. Although someone familiar with how to install and properly tension a cable transmission could fix this problem in a few hours, no one in the lab knows how. The WAM is returned for repairs that take 1 month, and the paper deadline is missed. As another example, perhaps the student is going to attach a custom 1-DOF gripper with a 1-DOF motorized laser-scanner to the WAM. Without much mechanical experience, the student will likely take a long time to design and fabricate the mechanism, only to discover that the backlash in the gears used in the laser-pan mechanism causes the data to be unusable. While the time spent fixing robots and iterating on failed designs is not a total waste as, hopefully, it was a learning experience, this effort is not towards the core of most students' research. If we teach students how to design and build mechanical systems effectively and efficiently, they will be able to spend more time on research and less time maintaining, modifying, and developing the infrastructure to do that research.

We propose to plug this knowledge gap by developing a hands-on, lab-based mechanical design course that teaches students most of the practical knowledge and experience required to design, build, modify, and repair robots. This is a hard task. How do you help a student to understand intuitively why backlash is bad and that bearings should be used in pairs, rather than merely stating these as points in a lecture? The educational innovation in this class is figuring out how to impart not only mechanical knowledge to students, but mechanical intuition.

Developing mechanical intuition requires that students touch and play with the mechanisms. For every new topic, each student will be handed prototypes during lecture so that he/she can feel the mechanism while we discuss it. The prototypes will include examples of proper and improper design so that students can feel the results of common mistakes. Example prototypes include

- Gears that have been spaced properly, too far apart, and too close

- Belts that are tensioned properly, too tight, and too loose
- Rotary shafts that are supported by two bearings and preloaded, supported by only 1 bearing, and supported by two bearings but not preloaded.

Lectures will consist of teaching students common applications for the mechanical components, proper usage, any practical equations or design graphs, the concerns and improper usage demonstrated in the prototypes, how to select various parameters for a particular part (e.g. gear/belt pitch, capstan diameter, and motor winding), and where to buy the components.

After students have felt a mechanism, they must build it. Each week, the students will prototype relevant applications of the mechanisms and components they have been taught in lecture. To help motivate their usefulness, mechanisms will be used to perform common, useful robotic tasks. For instance, rather than simply placing two gears next to each other on a block, the students will use gears to drive a 1-DOF gripper. Core concepts will appear in multiple labs so as to reinforce learning and develop intuition through repetition. For instance, students will have to install and preload pairs of bearings in all of the separate transmission prototypes that require a rotating shaft (e.g. belt, cable, gear, and friction drives). Students will keep these prototypes as future design references. The bulk of the prototyping will use the lab laser-cutter and 3D printing services to reduce prototyping cost and time, as well as give students experience in precision rapid-prototyping, instead of having parts machined. Students will drive their mechanisms with example code and plug-and-play motor drivers that are borrowed from the course to reduce electronics and software overhead. The capstone project for the course will consist of building a robot that uses as many of the mechanical components and mechanisms taught in the course as possible. Students who already need to build a specific design as part of research will be encouraged to build some version of that design for the project.

An important part of designing is knowing where to source components. Our long-term goal is to establish corporate sponsorships with companies such as McMaster, Bosch, Maxon Motors, and Misumi, wherein they provide many of the parts for free or at a significant discount. Students will actually select and order the parts themselves so that they become familiar with the complicated sourcing process, and the company/course will pay for the parts within a budget. Maxon Motors and HP have a similar relationship with the ME218 mechatronics course, and Misumi has already expressed interest in being involved in this new course. Until such sponsorship can be firmly established, the course will pay for the components that the students order within a budget.

The following is a preliminary list of topics to be covered in the course:

- Motors (DC, brushless, stepper, servo, and ultrasonic)
- Other actuators (pneumatic, hydraulic, piezoelectric, SMA, and solenoids)
- Position/velocity sensing (quadrature/absolute encoders, homing flags, and tachometers)
- Mechanical transmission (gears, belts, cables, friction rollers, and universal/flex couplers)
- Rotary and linear motion (bearings, bushings, splines, rack and pinion, and screws)
- Counterbalancing (gravity and springs)
- Framing (80-20 and vibration isolation)
- Wheels (pneumatic, solid, shocks, and treads)
- Design for safety and robustness (joint limits, clutches, brakes, pinch points, and covers)
- Standard mechanisms (4-bar parallelogram, remote center of motion, differential, wrist design, and gripper design)