MAKER: Designing and Building the Classical Inverted Pendulum on a Cart

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MAKER: Designing and Building a Two-DOF Inverted Pendulum on Three-DOF Cart

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Abstract: This paper describes the design and build of a pedagogical setup consisting of a two-DOF inverted pendulum, which is mounted on a three-DOF cart. This was a collaborative project between senior students in the departments of mechanical and electrical engineering at the United Arab Emirates University as part of their senior design capstone project. The students with guidance from their faculty mentors followed the various designing and building stages of the design process of the involved mechatronics system. This includes the steps of designing the setup, the building of the prototype, and the testing and verification of the prototype's subsystems.

1. Introduction

The inverted pendulum system is an example commonly found in control system textbooks and research literature. Balancing of an inverted pendulum on a cart has become a classical problem used in teaching control engineering, and for evaluating controller designs for under-actuated systems. This is due to the presence of interesting dynamical characteristics associated with the system including nonlinearity, instability, and under-actuation [1, 2, 3, 4]. Various designs of inverted pendulum mobile robots were introduced recently, for example [5]. The objective of the control system in this project is to balance the inverted pendulum by applying a force to the cart that the pendulum is attached to. Building an experimental setup for hands-on teaching of mechatronics control engineering is usually possible using low-cost resources and the authors are of the firm belief that in-house development of pedagogical setups in control and mechatronics labs greatly enhances the learning experience of the students. In this setup we have taken the problem to a higher level by increasing the degrees-of-freedom in the system to five, three associated with the cart and two associated with the pendulum. The interesting features of this setup are that the pendulum has two measured but unactuated degrees of freedom relative to the cart and the cart in turn is actuated along two directions in the horizontal plane. An Arduino based controller is employed to stabilize the pendulum in an upright position while moving the cart remotely. The project is carried out as a senior design graduation project by an interdisciplinary team consisting of four students from the departments of mechanical and electrical engineering at our United Arab Emirates University, UAEU [4]. The special features and challenging parts of the project, the students' experience and the lessons learnt from the project, are described in the rest of this paper. The poster of the prototype will show the achievements in the project.

2. The Design Process

The respective capstone course description, in the college of engineering at UAEU, requires that the students' design team perform detailed design and cost estimate of the selected alternative solutions to a well-defined engineering problem. The student team should apply knowledge gained throughout their studies to this challenging engineering design project. They also fulfilled the requirement of emphasizing creativity and originality in the solution adapted. Figure 1 depicts the design process that was followed [6]. The design process started with a literature search to comprehend the state of the art. This was followed by formulating the problem, identifying the requirements and setting target specifications. The specifications were firmed up after the completion of conceptual design. During the conceptual design stage alternative design concepts for various components and subsystems were proposed in the form of hand sketches as shown in Figure 2. In this manner several preliminary concepts, for mechanical and locomotion subsystem, controller, communication, human machine interface (HMI), and the 2-DOF pendulum joint, were proposed. The conceptual design stage that requires coming up with alternative solutions was carried out after formulating the problem, defining the requirements and setting rough specifications. The alternative design for the various components and subsystems were done mostly using hand sketching as shown in Figure 2. Preliminary designs for the different subsystems including the mechanical and locomotion, the controller, the communication, the human machine interface (HMI), and the sensed 2-DOF pendulum joint, were also developed and designed as such.

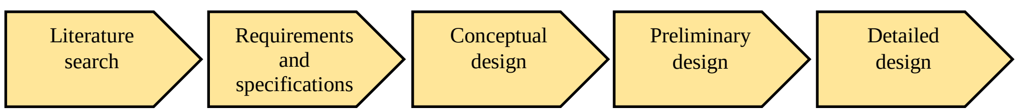

Figure 1: The design process flow chart

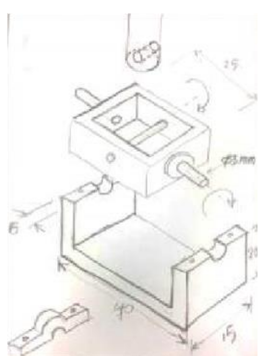

Figure 2: Hand sketching of components and subsystems [4]

The team then went on to complete the detailed design consisting of detailed working drawings, wiring diagrams and component selection for the controller and communication subsystems. As the implemented design process is iterative in nature, refinement of the concept design, and the subsequent stages are needed at various stages of the design process. For example, the solid model of an initial design of the assembled prototype is shown in Figure 3. In this design, a provision to use an inertial measurement unit (IMU) to estimate the tilting angles was provided. This specific feature in the design was later changed to include direct measurement of the angles using potentiometers, as can be seen in the actual prototype depicted by Figure 4. Detailed drawings of the parts were prepared using the CATIA solid modeling package. This facilitated the use of 3D-printing for manufacturing several components used in the prototype. Figure 6 shows an example, the pendulum joint yoke, as the solid model and the working drawing. This part and the second yoke of the universal joint were 3D printed from PLA plastic material.

3. The prototype

The prototype consists of 1) the mechanical structure, 2) the electronics and control subsystem, and 3) the software design.

3.1 The mechanical structure

After completing the detail design, the porotype was manufactured and assembled. As shown in Figure 4, the cart is a mobile robot that has three-DOF, two of them are translational in the horizontal plane, and one rotational about the vertical direction. This is achieved by the use of four Omni wheels, which are driven by four geared dc motors. The pendulum is placed on the upper platform through a two-DOF joint. The two motion components are passive and are measured using two potentiometers on the two axes of the joint, as shown in Figure 4.

Figure 3: Solid model of an intermediate version of the built prototype [4]

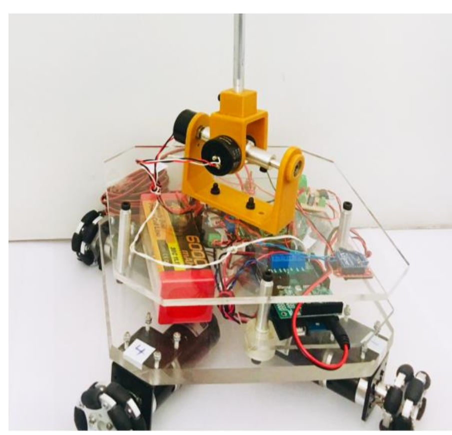

Figure 4: The built prototype [4]

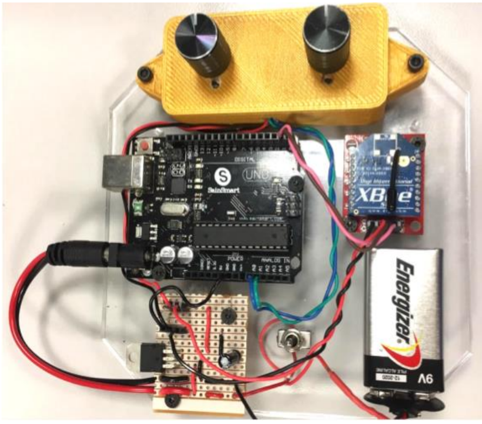

Figure 5: The remote control prototype [4]

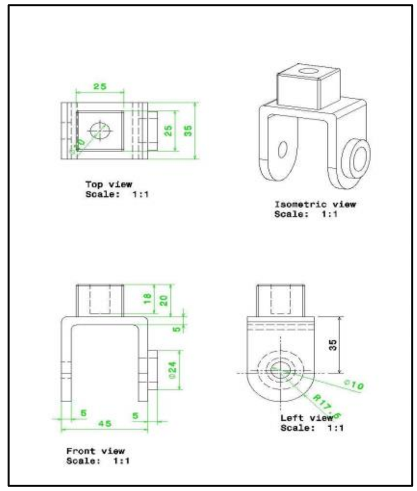

Figure 6: Working drawing and solid model of the pendulum joint bracket [4]

3.2 The controller and the electronics

The design team proposed to implement a decoupled PD controller to control the orientation of the pendulum to keep it vertical. As shown in Figure 7, the students proposed a PD controller. This assumes that the translational motion components of the cart, align with the rotational directions of the pendulum. Thus, each motion of the pendulum is controlled independently. The angular position θ_i is measured using a respective potentiometer, differentiated to have the angular velocity ω_i. The electronics selected consists of an Arduino Mega microcontroller, two Pololu dual drives, XBee wireless communication module, and a voltage regulator board. The wireless communication is established with a remote controller that is also built in-house using an Arduino UNO, potentiometers, and XBee module, as shown in Figure 5.

The testing of the completed prototype and the various subsystems started as the last stage of the project. Figure 8 shows testing of the received signals through the wireless communication of the potentiometers' output voltages. Since the PD control requires availability of the angular velocity, the displacement is numerically differentiated using a low pass filter to reduce the effect of the noise that results from the numerical differentiation. The control of system along one direction is roughly achieved while restraining the tilting of the pendulum along the other direction. Controlling the two directions simultaneously is underway.

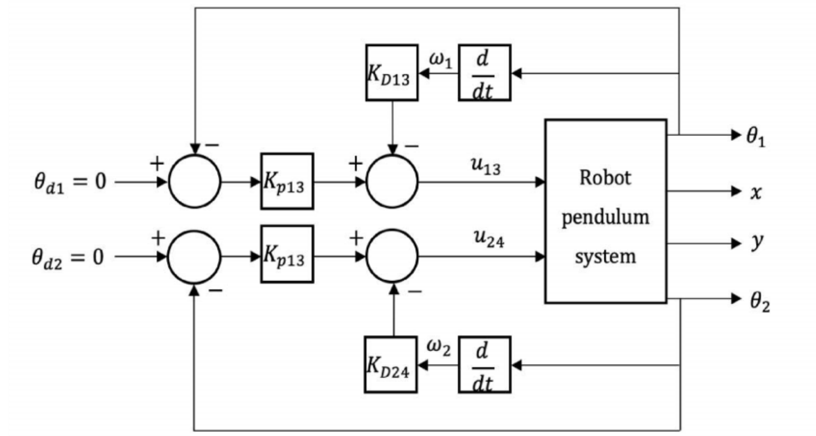

Figure 7: Initial control strategy- PD uncoupled control [4]

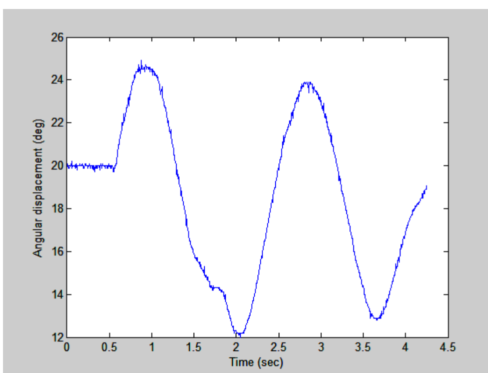

Figure 8: testing the potentiometers' outputs through the wireless

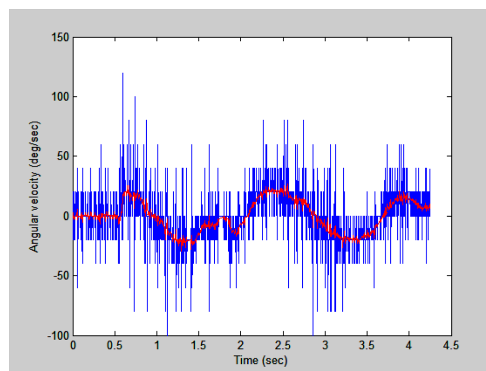

Figure 9: The angular velocity is obtained from the angular displacement signal using numerical differentiation, with and without a low pass filter

4. Remarks and Conclusions

The four students involved in the project are from two engineering programs, mechanical and electrical engineering, with different knowledge, experiences and skills, representing a perfect team to tackle such a development project. They moved through the various design and development stages applying the fundamentals of engineering-design and coming up with alternative solutions, preliminary and detailed designs. While working as a team, they resembled a typical work environment expected after graduation. As expressed by one of them, the opportunity to work on such a project was unique. The design and built prototype was completed successfully. Controllers that fully stabilize and command the system along all five degrees of freedom will be demonstrated in the poster presentation.

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