Modular Design for Inclusive and Accessible Mechatronic Educational Equipment

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Abstract

Mechatronics is an interdisciplinary engineering field studied by students with different prior knowledge and skills. To maintain the high quality of the mechatronics curricula and to enable inclusive educational processes, students should have the opportunity to learn independently using suitable teaching aids. Unlike theoretical content, applied engineering knowledge needs to be supported by real hardware. However, it is usually made subject-specific and has constrained access.

To meet the challenges of mechatronics education a modular servomotor, was developed as part of the Erasmus+ project GEMS. The designed equipment presented in this paper promises to provide students with better access to educational hardware that covers all core mechatronics domains and offers an equal chance of inclusion in mechatronics curricula.

1 Introduction

Mechatronics is an interdisciplinary field of study combining three core engineering domains [1]. Mechanical engineering, electrical engineering and computer science are studied in order to acquire the ability to design complex systems and innovative solutions. In the case of mechatronics, a balanced overview of different concepts and technologies is preferred over in-depth specialized knowledge. Mechatronics curricula should ideally guide and support a theoretical and practical education that gives students the opportunity to acquire balanced knowledge and skills from all three core engineering domains. Many types of teaching tools are used in the educational process of mechatronics. On the one hand, there are tools based on simulations and virtual environments, e.g. [2, 3]. On the other hand, there are hardware learning kits, e.g. [4], development microcontroller boards, e.g. [5] and educational setups with industrial equipment, e.g. [6]. Both sides are usually accompanied by now ubiquitous online educational platforms, e.g. [7] that support the exchange of written or video literature and independent learning with interactive applications.

The challenge in realizing the desired ideal of balanced engineering knowledge for all students of mechatronics curricula arises from the differences between higher education institutions and differences between the students of those institutions who will follow the curricula. The differences between institutions are primarily due to the fact that mechatronics curricula are primarily a continuation of the study of one of the core engineering domains. Thus, if a student is enrolled in a mechanical engineering faculty, the mechatronics program will provide the student with additional knowledge from the other two domains. The same is true for electrical engineering and computer science faculties. In practice, mechatronics students from different faculties will have differently balanced knowledge at the end of their studies, depending on the faculty domain. Even if this is not ideal, it is an understandable and acceptable situation.

Far less acceptable are the consequences resulting from the different prior knowledge of students following the same curriculum. The differences in prior knowledge mean that parts of the curriculum are overwhelming for some students and redundant for others. This means that the majority of students will find some parts of the whole curriculum difficult and will have to spend more time and effort to acquire the new knowledge. The time pressure imposed on educators prevents them from personally helping struggling students, so students have to do additional learning on their own. If the study problem is theoretical or is set in a digital or virtual environment, there are many tools that can help students overcome the problem. However, if the study problem requires interaction with real hardware, access to the equipment is most likely limited to a short time slots and an assigned room in the educational institution. Since resources are required to set up and maintain the hardware, the number and variety of educational hardware is also limited, reducing accessibility for an average student even during the scheduled time.

This article presents a solution of the Erasmus+ project GEMS: Graceful Equalizing of Mechatronics Students, which proposes a mechatronics education hardware with modular design and focus on accessibility. The modular design of the hardware [8] instead of the modular curriculum [9] promises to enable educators and students to pursue the ideal of balanced mechatronics knowledge by providing an accessible hardware foundation on which curricula that are the same for all students can be based and support the study process in a flexible way.

Flexibility in this context means the ability to use the hardware at the faculty or at home independently of other specialized equipment or supervision. It also means the possibility to use the modules independently or interconnected in a more complex system. Finally, the proposed hardware is designed to be affordable and easy to manufacture or modify. Modifications can be made at the level of components, individual modules or the entire system. With this kind of accessibility and flexibility of the educational hardware, all students who want to study mechatronics can be included, regardless of their previous knowledge or the resources of the educational institution.

The following chapter describes the modular design concept that formed the basis for the development of the hardware, focusing on the specifications and the design process. The practical implementation of the concept is then presented in the form of a modular servomotor that provides the hardware capabilities to support a balanced mechatronics education process. Finally, the potential of the developed hardware for use in mechatronics education is discussed.

2 Concept

Modular design is a systematic approach to breaking down complex systems into smaller, self-contained units or modules. These modules are designed to perform specific functions and interact with each other via well-defined interfaces. By breaking down a system into modular components, engineers can improve its manageability, flexibility and scalability. While modular design offers numerous benefits, it also brings challenges, such as increased system complexity and the need for effective interface management. Successful implementation requires careful consideration of module granularity, interface standards and overall system architecture.

2.1 Specifications

Specifications for mechatronic educational hardware designed for accessibility must consider many additional requirements that differ from the requirements for a consumer hardware product.

A single device developed for mechatronics education must contain functions from all core fields (mechanics, electronics and computer science). The device should be divided into modules that have different educational focuses, complement each other and can be integrated via a well-defined interface. A minimum list of modules was drawn up based on their functionality, including modules for power supply, sensors, actuator control, communication and mechanical mechanisms.

The device should be small enough to be easily transported and large enough so that all components can be easily observed, assembled or manufactured using processes accessible to educators or students. Therefore, the device should be easy to manufacture and repair by its users.

Due to the device's repairability, a phenomenon important to education may be emphasized at the expense of precision, efficiency, compactness or durability. For example, elements of the device may cause noise, heat, vibration or surface wear or even break. Elements that break or wear out can be considered a learning experience and not something to be avoided, as is the case with more expensive purchased equipment. Nevertheless, each module on its own and the assembled device must be safe to use without supervision.

2.2 Design process

The proposed design process for mechatronic educational hardware consists of two successive phases, which are shown in figure 1. The first phase, which begins after the specifications have been defined, is the exploration phase and the following phase is the consolidation phase, which ends with a final design. The design process uses elements of the axiomatic design methodology [10, 11] in a less formal way that focuses more on iterative exploration while striving for independence of functional requirements and simplicity of design to produce a robust and reliable system.

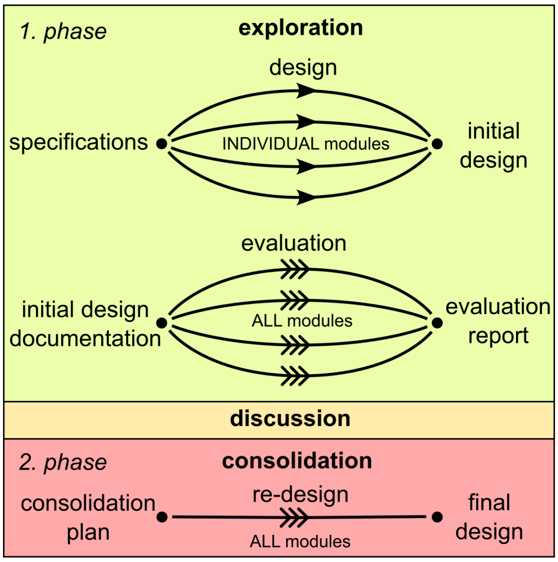

Figure 1: Two stage design process of a modular educational hardware.

In the first phase of the design process, the identified modules are developed freely and independently to explore different possible solutions within the specification limits. The exploration process is most effective when the modules are developed by different teams who can exchange ideas and keep the design of the modules loosely coupled. First, the hardware for each module is designed and documented. Then the software required to demonstrate the hardware functions is developed. At the end of the first phase, each development team, in collaboration with a group of students, recreates the designs of all the other teams and evaluates them in an evaluation report.

Between the first and second phase, all design teams discuss the results of the first phase and create a plan for design consolidation in the second phase.

The goal of the second phase is to create a final design for all modules that can be combined in a functioning device. The consolidation phase builds on the experiences and discoveries of the first phase. Features and functionalities common to all modules are standardised, while essential elements of the modules are emphasised. Particular attention is paid to the manufacturing process of the modules so that they can be easily manufactured, assembled, repaired or replaced. The use of concise technical notation and documentation with a clear, consistent style should be used for all modules, as this proves to be particularly important for a good user experience.

3 Implementation

The two-phase design process was used for the design of the educational hardware within the Erasmus+ project GEMS: ”Graceful Equalising of Mechatronics Students” by a partnership of four educational institutions:

- University of Ljubljana
- University of Alcalá
- Teaching Factory Competence Center
- Delft University of Technology

3.1 Specifications

A servomotor was chosen as an educational hardware because it can be used as a case study in most mechatronics subjects. The functionality of the servomotor was described as the ability to:

- control rotation of the output shaft driven by a DC motor with high reduction gearbox
- sense its environment and extract useful information
- communicate and integrate with other devices (focus on industrial equipment)
- have battery based power supply autonomy

The approximate size of the servomotor was defined as a cube with a side length of 10 cm. The components of the servomotor were limited to common standard mechanical and electrical elements, double-layered circuit boards designed for hand soldering, and parts that can be FDM 3D printed using single material and with minimal post-processing.

3.2 Design process

The design process of the modules was divided among the GEMS project partners during the exploration phase. Each partner team was able to independently develop an initial module design with associated demonstration software based on the specifications. The teams exchanged progress reports at regular intervals and discussed different design solutions. Documentation for the initial design of each module was also created independently by each team, with the goal of making their design reproducible for engineering students. Based on this documentation, a group of students and educators at each partner institution fabricated all modules, used them to assemble the servomotor, and thus evaluated the design, compatibility, and effectiveness of the modules' documentation.

At the end of the exploration phase, the project team discovered many design features that needed to be improved. The first important finding was that while some solutions are technically correct and improve the operation of the entire system, they also greatly increase the complexity of the modules, e.g. a circuit for voltage increase to a constant value from a single cell battery power supply. The second finding was that while stacking sub-modules on a module using connectors has its benefits, these are outweighed by the increased thickness of the module and reduced robustness. The third realisation was that size 1206 is the smallest size of passive SMD component that an average inexperienced student can comfortably solder by hand. Some implementations of USB-C connectors also proved to be particularly difficult to solder and were in final design avoided. The fourth finding was that the tolerances of the 3D printed parts were more difficult to achieve than originally anticipated. This was particularly problematic when tight tolerances were required, such as gear pairs and nut slots.

In the consolidation phase these finding were used to re-design all the modules and create the final design. The re-design was done by as single small team that focused on producing a unified module design.

3.3 Modules

The final design of servomotor shown in figure 2 is divided into five modules: Power supply module (Emerald), sensor module (Ruby), communication module (Sapphire), control module (Diamond) and drivetrain module. Four modules are realised with PCBs and one with 3D-printed parts. The four PCB modules are named after precious gemstones and are connected in a daisy chain. They share the battery power supply and a CAN bus. Each PCB is attached to one edge of the drivetrain base. The drivetrain module's DC motor and rotation control sensors are connected to the control module. Each of the four PCB modules has a 3.3 V microcontroller that can be powered and programmed via USB-C. All microcontrollers are able to communicate wirelessly via WiFi or Bluetooth.

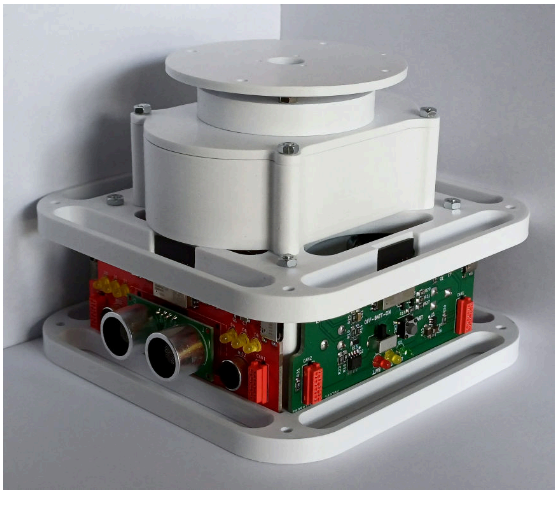

Figure 2: GEMS modular servomotor.

3.3.1 *Power supply module*

The power supply module shown in figure 3 provides power autonomy to the servomotor based on standard 1-cell 18650 Li-ion battery with a nominal voltage of 3.7 V. The module has a USB charging circuit, reverse polarity protection, overcurrent protection and manual activation/deactivation. The battery status is displayed via 3 LEDs. The integrated ESP32-C3 microcontroller also enables the measurement of battery voltage and current, which can be shared with other modules.

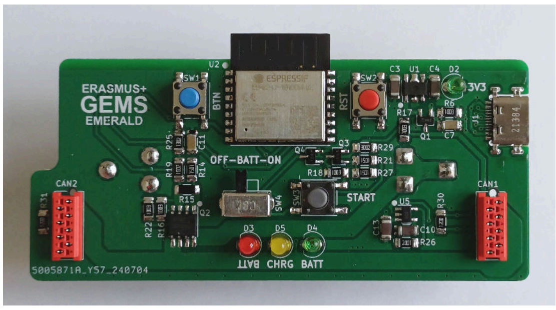

Figure 3: GEMS Emerald: Power supply module.

3.3.2 *Sensor module*

The sensor module shown in the figure 4 uses sound-based sensors and an ESP32-C3 microcontroller to monitor the servomotor's environment. An HC-SR04 compatible ultrasound sensor submodule is used to measure the distance between the servomotor and nearby objects. The measurement can be displayed via six onboard LEDs or used as a reference for the motor control. Two audible range microphones spaced 55 mm apart can be used to determine the direction of a sound source or to analyse the sound generated by the drivetrain.

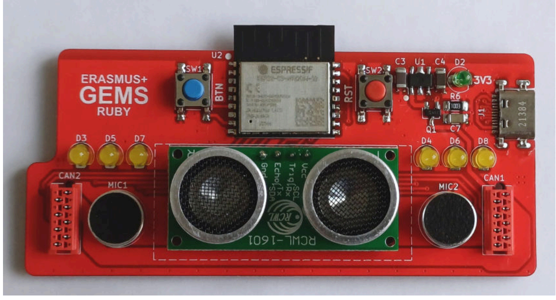

Figure 4: GEMS Ruby: Sensor module.

3.3.3 *Communication module*

The purpose of the communication module shown in the figure 5 is to give the user access to information about the servomotor and to enable remote control. The module uses an ESP32-S3 dual-core microcontroller that supports wireless communication via WiFi and Bluetooth with consumer devices (e.g. smartphone, PC) and networked industrial equipment. Wired communication is possible via CAN, I2C or UART. The information can be shown on a small OLED display or signalled with a piezo buzzer.

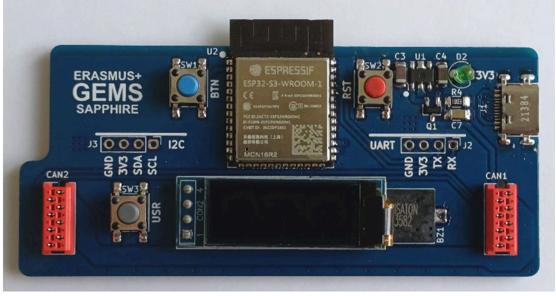

Figure 5: GEMS Sapphire: Communication module.

3.3.4 *Control module*

The control module shown in figure 6 is used to control the DC motor in the drivetrain with an ESP32-S3 dual-core microcontroller. Feedback is provided by three Hall effect sensors. Two sensors are used to measure the motor speed and direction of rotation. The third sensor is used to determine the reference position on the output shaft. The motor is controlled via an H-bridge with 4A current limitation and the current is measured with a Hall-based current sensor. Three LEDs are used to indicate the controller status.

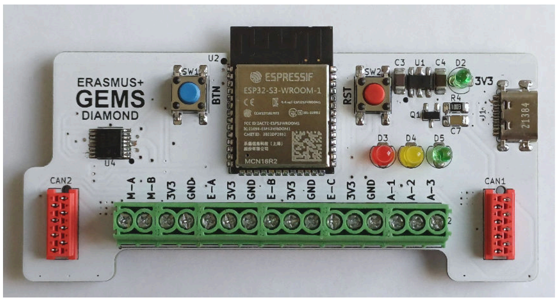

Figure 6: GEMS Diamond: Control module.

3.3.5 *Drivetrain module*

The drivetrain module, which is also shown in figure 2 as part of the whole system, consists of three parts. The first part is the base, which holds the four PCB modules and the DC motor with a gear, two magnets and Hall sensors. The first part can be used independently if no speed reduction is required. The second part, shown in figure 7, is the gearbox, which contains five reduction stages in overall ratio of 243:1. The third part is the specially developed bearing with an output shaft. The parts of the drivetrain are manufactured using a FDM 3D printer and standard parts (⌀6 bearing balls, M3 screws and nuts, ⌀3 dowel pins. The drivetrain is designed so that the two servomotors can be easily combined to create a simple mobile or articulated robot.

Figure 7: GEMS Drivetrain: Gearbox.

4 Discussion

The modular servomotor has been designed to be fully usable in mechatronics curricula. It can be manufactured in educational institutions by educators or students who have basic soldering equipment, access to a FDM 3D printer and a PCB manufacturing service. The manufacturing process itself can be educational for students who don't have much experience with manufacturing, giving them the opportunity to learn skills that other students may already have. These skills are useful when the servomotor needs to be repaired. Since the servomotor is easy to make or repair, it can be given to students for independent use in the classroom or at home without much concern.

This significantly enhances the availability of hardware for students who require it to acquire a specific aspect of the mechatronics curriculum. There may be several reasons why a student would want to use educational equipment outside the classroom. A student, for example, was unable to attend the laboratory tutorials and wanted to compensate for the missed opportunity. Some students may require additional time to acquire the required knowledge. Some students can't regularly attend classes or tutorials because of medical condition or are active athletes, but still want to follow the curricula with their peers. All these situations become manageable if sufficient available educational hardware could be loaned to students. These students remain included in a group of peers who follow the same quality curriculum.

The presented modular servomotor is one possible educational hardware that could improve the outcome of mechatronics curricula by giving all students equal opportunity to study. The described design process provides an example of successful development of a balanced educational mechatronic device, and can serve as a guideline for creating another. However, the effectiveness of the developed servomotor as an accessible educational hardware will need to be empirically verified by using it in a real mechatronics curriculum.

5 Acknowledgment

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5.1 Disclaimer

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