Teaching Robotic and Biomechatronic Concepts with a Gripper Design Project and a Grasping and Manipulation Competition

Minas Liarokapis and George P. Kontoudis

***Abstract*— Lecturers of Engineering courses around the world are struggling to increase the engagement of students through the introduction of appropriate hands-on activities and assignments. In Biomechatronics and Robotics courses these assignments typically focus on how certain devices are designed, modelled, fabricated, or controlled. The hardware for these assignments is usually purchased by some external vendor and the students only get the chance to analyze it or program it, so as to execute a useful task (e.g., programming mobile robots to perform path following tasks). Student engagement can be increased by instructing the students to prepare the hardware for their assignment. This also increases the sense of ownership of the project outcomes. In this paper, we present how a robotic gripper / hand design project and the introduction of a grasping and manipulation competition as a course assignment, can significantly increase the student engagement and their understanding of the taught concepts. The presented best practices have been trialed over the last four years in two different courses (one undergraduate and one postgraduate) of the Department of Mechanical Engineering at the University of Auckland in New Zealand. For the particular assignment the students were asked to fully develop a robotic gripper or hand from scratch using a single actuator (only the actuator and the power electronics were provided). The performance of the developed devices was assessed through the participation in a grasping and manipulation competition. All the details of the proposed assignment are presented, hoping that they could help other lecturers and teachers to prepare similar activities.**

I. Introduction

Increasing student engagement in Engineering courses and students appreciation and understanding of the materials taught is a challenging task that necessitates the introduction of appropriate hands-on activities and assignments. Over the last four years (2017-2020) in the Department of Mechanical Engineering at the University of Auckland (New Zealand), we have been trialling a new type of assignment that combines a gripper design project and a grasping and manipulation competition in order to teach undergraduate and postgraduate students particular robotics and biomechatronics concepts. Examples include contact modelling, robot grasping and manipulation, principles of differential mechanisms, modelling and design of underactuated systems, and Electromyography based control. The assignment is called "Biomechatronics Research Project" and the students are asked to design, develop, and control a complete robotic gripper or hand from scratch. Only a single actuator and the required power electronics are provided.

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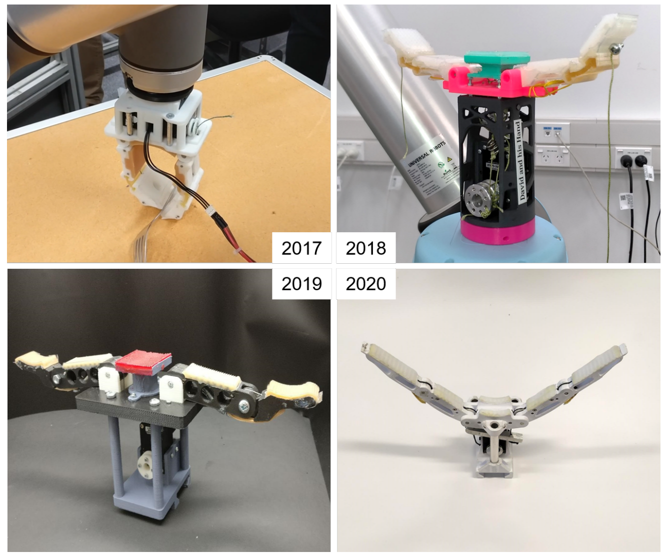

Fig. 1. The winning robotic gripper designs of the 2017, 2018, 2019, and 2020 Grasping and Manipulation Competitions of the proposed assignment, are presented.

The performance of the developed device is assessed through the participation in a robotic grasping and manipulation competition in which the students are called to grasp a plethora of everyday life objects with the developed grippers and hands. If the grasps are successful the students get the corresponding marks. Thus, the lecturer is not involved in the gripper assessment process, decreasing grading subjectivity. Two subsidiary hands-on activities that take place in the lab have been designed so as to support the efforts of the students. One of these activities focuses on the demonstration of a hybrid manufacturing method that is useful for the development of adaptive robotic grippers and hands, while the second activity focuses on real life applications of the theory taught and it involves a range of lab demonstrations focusing on state-of-the-art research.

The proposed assignment: i) increases student understanding of the taught material, ii) helps students understand how the taught theory relates to the system performance, iii) increases student engagement in the class, iv) helps students develop a "can do" attitude by creating a complete robotic / biomechatronic device, v) increases sense of ownership of the project outcomes. The feedback from the Summative Evaluation Tool (SET) surveys (teaching assessment surveys) over the last four years demonstrates that the students appreciate hands-on projects and experiences, especially when they involve some kind of competition.

Furthermore, an increasing number of students becomes passionate about the subject and many of these students continue working on similar topics for their post-graduate studies (e.g., past participants are now PhD students working on similar topics).

A. Assignment Motivation

The markets of robotics and prosthetics are dominated by rigid, fully-actuated, heavy, and expensive devices. For example, most robot and prosthetic hands cost between $20,000 and $100,000, while requiring considerable effort and expenses to be repaired and maintained [1]. The fear of damaging the prostheses, as well as the lack of dexterity and the difficulties they face operating the devices lead most amputees to avoid using sophisticated devices in everyday life tasks and use instead simple body-powered hooks, grippers, simple cosmetic hands, or even the arm without a prosthesis [2]. In addition, amputees prioritize dexterity and affordability over appearance [3]. As a result, the commercially available, expensive prostheses are rarely used and most of the time they end up in a drawer [2]. To this end, amputees need affordable, dexterous, robust, and lightweight solutions that can be easily fabricated, maintained, and repaired. The aforementioned status of the prosthetics market introduces to the students a real-world challenge that could potentially have a real-life impact. Students appreciate to be challenged with a "hands-on" assignment that could potentially have such real-life applications.

B. Adaptive Robot Grippers and Hands

Grasping and dexterous manipulation allow humans to efficiently interact with their surroundings and execute meaningful tasks (e.g., grasp complex objects, push buttons, etc.). In the fields of robotics and prosthetics, such complex tasks are typically accomplished by rigid, fully-actuated, multi-fingered devices that need sophisticated sensing elements and require complex control laws. Despite the numerous studies and gripper / hand designs that have been proposed over the last decades, the field has not seen significant progress in terms of practical, real-life applications of robot grasping and manipulation. Even the notion of robotic dexterity remains hard to define, quantify, and accomplish. To attempt to address this problem, researchers were inspired by postural hand synergies which describe human hand motion couplings during grasping and manipulation [4]–[6]. This led to the development of synergy-based robot hands where a substantially lower number of actuators was used to control postural hand synergies [7]–[11]. Recently, another alternative paradigm to the fully-actuated, rigid robotic mechanisms that are heavy and expensive has been proposed. Adaptive (i.e., underactuated and compliant) robotic hardware is of low complexity, weight, cost, and is being designed to simplify the execution of complex operations and tasks such as grasping and dexterous manipulation [12]–[21]. The passive adaptability of these mechanisms that arises from the under-actuation and the structural compliance offers excellent conformability to the shape of the grasped objects maximizing grasp stability and robustness [22], [23]. Due to the aforementioned advantages of adaptive grippers and hands, the proposed design assignment focuses on tendon-driven mechanisms that can be controlled by a single actuator, employing appropriate differential mechanisms [24]. This design choice also reduces the budget required for the implementation of the required grippers. The students are instructed that their devices should be as affordable and lightweight as possible and that they should exclusively use rapid prototyping equipment and hybrid manufacturing techniques [25] to develop them with low-cost materials.

The rest of the paper is organized as follows: Section II introduces the related work, Section III describes the proposed assignment, Section IV presents the Grasping and Manipulation Competition, Section V presents and discusses the results, while Section VI concludes the paper.

II. Related Work

Educational robotic platforms have received considerable attention in recent years, as they can offer effective and constructive educational tools and methodologies for teaching STEM related courses or to cover topics related to the interdisciplinary fields of robotics and automation. Platforms include self-driving, small-scale cars [26]–[29], desktop robots [30], [31], mobile manipulators [32], [33], and miniature robots [34] to name a few. These platforms incorporate sensors and embedded computers so that they can be used for a wide range of applications. Inter-robot communications facilitate the implementation of decentralized algorithms in [27], [28], [30]–[34]. Onboard cameras enable vision experiments in [27]–[31], [33]. A demonstration of deep learning techniques with cloud integration is discussed in [28], while in [29] an external GPU is used to alleviate the robots from expensive computations. Pheeno is equipped with a toy gripper for grasping of small objects [33]. Multi-robot manipulation can be achieved with r-one robots [32]. In particular, the latter use gripper paddles that are mounted radially in order to collaboratively translate and rotate objects of specific geometry. However, all these platforms cannot execute robust grasping and dexterous manipulation tasks of everyday life objects. Additionally, modifications of the mechanical design are not possible. Thus, the majority of the existing robotic platforms are used for the implementation of robotic algorithms and cannot be employed for teaching mechanical design, sensor integration, and fabrication concepts.

Integration of competitions in education is a useful assessment tool. Although competitions concentrate on winning strategies and competitiveness that could contradict learning objectives, a proper structure promotes intellectual development based on the Perry model [35]. Moreover, mature students accept that an open-ended, complicated problem can be addressed in multiple ways, providing various solutions [36]. Thus, a student competition should be clearly motivated and designed so that several solutions can be accepted. In [37], a student robotic competition is developed for a fire-fighting scenario. A bullfighting robotic competition, termed as Cybertech, is discussed in [38]. Students are assigned to build bullfighter robots and compete against a bull robot with certain capabilities, which is provided by the instructors. A robotic decathlon competition is developed as a series of 10 project-based labs in [39]. In the first two parts of the competition, a robotic arm with a toy gripper is provided for simple grasping and manipulation tasks. The use of soft materials sets new standards for intelligent adaptive systems. Thus, a soft robotics design competition for robotic locomotion is proposed in [40]. Furthermore, additive manufacturing is another emerging field that facilitates affordable, rapid prototyping and fabrication. In [41], a student competition is proposed for robotic manipulator design and development using 3D printing. These manipulators are then used for the execution of trajectory planning tasks. However, there is no competition focused on robot gripper / hand design and development or on robot grasping and dexterous manipulation.

III. The Assignment

In this section we present the different components of the "Biomechatronics Research Project" assignment that was used from 2017 to 2020 in the following two courses of the Department of Mechanical Engineering at the University of Auckland (New Zealand):

- MECHENG 736: Biomechatronics Systems - Undegraduate Course (Year 4, Mechatronics Engineering)
- MECHENG 730: Advanced Biomechatronic Systems - Postgraduate Course

A. Project Deliverables

All undergraduate students are asked to work in groups of three. All postgraduate students work alone. Each group or postgraduate student is expected to deliver:

1) A working prototype of a robotic hand or gripper that will participate in the Robotic Grasping and Manipulation Competition for assessment purposes.
2) An oral presentation (5 min presentation for each undergraduate student and 15 min presentation for each postgraduate student).
3) A video demonstrating the efficiency of the developed device. The video needs to be self-explanatory and to be included in the project report.

Each student is expected to deliver an individual research report describing the developed hand / gripper using an IEEE template. The report length should be at least 4 pages and not exceeding 6 pages with font size 11pt, including references. The structure of the report may contain the following sections: Introduction, Related Work (or Literature Review), Methods, Designs, Experimental Validation, Discussion, Conclusions, and References. Note that the proposed structure is not mandatory.

B. Assessment

The project assessment is performed as follows:

1) The prototype functionality is worth 50% of the project grade. The functionality is demonstrated through the participation in the demonstration sessions of the grasping and manipulation competition (40%) and the self-explanatory video that is submitted with the report (10%). The objects that are used for the grasping and manipulation competition are: a washer, a marble, a fork, pliers, a credit card, a chain, a hammer, a wrench, a drill, and a 1.5 L bottle of water (see. Fig. 2).
2) The report is worth 30% of the project grade.
3) The presentation style of the self-explanatory video is worth 10% of the project grade. This component focuses on the video presentation quality and aesthetics.
4) The oral presentation is assessed individually and is worth 10% of the project grade. The presentations take place before the start of each demonstration session.

Fig. 2. The objects that have been used in the Grasping and Manipulation Competitions.

C. Bonus marks

The following bonus marks are employed to encourage students to explore new design concepts and to increase the performance and the capabilities of their grippers / hands. These bonus marks concern only the grasping and manipulation competition and are as follows:

- The best design (the winner of the grasping and manipulation competition) receives an extra 10% bonus.
- A novel design receives an extra 10% bonus. Novelty needs to be justified with respect to the state of the art.
- The most lightweight design receives an extra 10% bonus if it also performs better than the average design.
- An anthropomorphic, five-fingered robot hand receives a 10% bonus.
- A hand capable of executing a dexterous, in-hand manipulation motion with a single actuator receives an extra 20% bonus.

Note that all these bonus percentages apply only to the prototype functionality marks.

TABLE I

TABLE I. CHARACTERISTICS AND PERFORMANCE METRICS OF THE DEVELOPED GRIPPERS AND HANDS. THE * DENOTES MISSING CHARACTERISTICS.

Characteristics	2017	2018	2019	2020
Average Weight	*	507.1 g	552.2 g	487.1 g
Heaviest Gripper	*	1,002 g	791 g	934.2 g
Total Weight (All grippers / hands)	*	12,677 g	12,148 g	11,590.6 g
# Grippers / Hands	14	25	25	26
# Spring Loaded Pin Joint Designs	6	16	13	16
# Hybrid Designs	5	6	10	10
# Flexure Joint Designs	3	3	2	0
# Anthropomorphic Hands	0	2	2	5
Dexterous Manipulation Capabilities	2	2	0	0

Metrics	2017	2018	2019	2020
Average Success Rates	72.9%	82.3%	83.5%	95.7%
% of teams with perfect score (100%)	21.4% (3/14)	16% (4/25)	24% (6/25)	73.1% (19/26)

D. Confidential Peer Assessment

All members of each student group are expected to contribute equally and fairly towards the successful completion of the different project components. Each member is required to fill out a confidential Peer Assessment (PA) form and upload it on the course website (e.g., Canvas page). The completion of the PA form intents to identify the level of contribution of each partner to the group project.

E. Late Submissions

Late submissions are automatically flagged by Canvas. Resubmitting after the deadline incurs late submission penalties. A late PA submission also incurs late submission penalties that are applied individually (not affecting the marks of the partners). The following penalties are applied for late group submissions and PA submissions (individual penalty):

- Up to 1 hour late: 10%
- 1 hour to 1 day late: 25%
- 1 to 2 days late: 50%
- 2 or more days: 100%

F. Biomechatronics Research Project Timeline

The "Biomechatronics Research Project" assignment has a total duration of 11 weeks. A brief outline of the research project timeline is as follows:

- Project announcement: Day #1 of Semester
- Practice Sessions: Week #8 of Semester
- Demonstration Sessions: Week #10 of Semester
- Project Report Submission: Week #11 of Semester
- PA Submission: Week #11 of Semester

IV. GRASPING AND MANIPULATION COMPETITION

A. Practice Sessions

The practice sessions give the opportunity to the students to test their grippers using the provided power electronics, appropriate GUI based control interfaces and their own control schemes, as well as to attach their grippers / hands on the Universal Robots UR5 and UR10 robot arms that are used for the Grasping and Manipulation Competition.

B. Demonstration Sessions

The actual Robotic Grasping and Manipulation Competition takes place during the "Demonstration Sessions". The procedure that the Teaching Assistants (TAs) follow for the demonstration sessions is:

1) The students attach the developed robotic hand / gripper on the UR robot arm (UR5 or UR10).
2) Each object lies in a predefined position (by the TAs).
3) The students can preposition the UR robot arm using the gravity compensation mode.
4) The students decide an appropriate position for the robotic hand / gripper.
5) The students control the robotic hand / gripper to grasp the object.
6) The TAs move the UR robot arm away from the initial position (using the teach pendant).
7) Grasp Evaluation: If the grasp remains stable for 10 seconds after the repositioning, the students get the grasping points.
8) For every grasp the students have a total of 3 attempts.

The objects used for the demonstration sessions are: a big bottle of water (full, 1.5 lt), a credit card (flat on a table surface), a fork, a washer (flat on a table surface), a wrench, a drill, a hammer, and a chain (articulated object).

V. RESULTS

In this section we present the results of the proposed Robotic Grasping and Manipulation Challenge for the academic years 2017, 2018, 2019, and 2020.

A. Characteristics and Performance Metrics

Table I presents the characteristics and the performance metrics used for evaluating the developed grippers and hands. It can be noticed that over the years students develop devices of similar weight, although the design choices change significantly. More precisely, we have a percentage decrease of flexure joint designs and a percentage increase of hybrid designs that combine flexure joints and spring loaded pin joints, as well as an increase of the percentage of the designs that use only spring loaded pin joints.

Fig. 3. All the robotic grippers and hands that were developed for the 2017, 2018, 2019, and 2020 Grasping and Manipulation Competitions are presented.

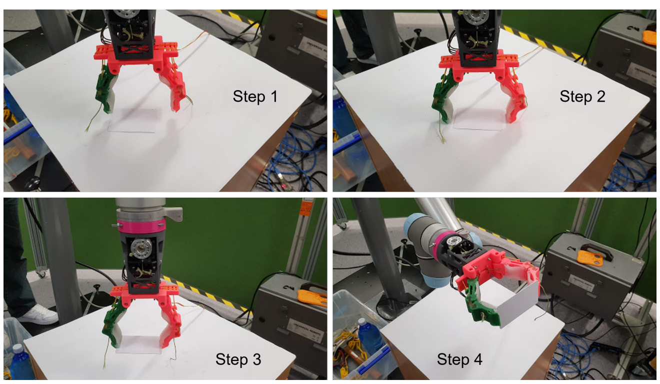

Fig. 4. The steps used during the demonstration sessions of the Grasping and Manipulation Competition for grasping and reorienting the object.

TABLE II

TABLE II. SUCCESS RATES OF DEVELOPED GRIPPERS AND HANDS IN GRASPING VARIOUS EVERYDAY LIFE OBJECTS. THE * DENOTES THAT THE OBJECT WAS NOT USED IN THAT YEAR.

Objects	2017	2018	2019	2020
Washer	64.3%	76%	68%	88.5%
Marble	85.7%	100%	100%	*
Fork	85.7%	100%	100%	96.2%
Pliers	42.9%	100%	60%	*
Credit Card	100%	96%	96%	100%
Chain	50%	96%	88%	100%
Hammer	57.1%	36%	76%	100%
Wrench	78.6%	72%	88%	96.2%
Drill	100%	100%	96%	100%
1.5 L Bottle of Water	64.3%	44%	56%	84.6%

This is due to the fact that students are informed about the mistakes made by students in previous years. Such mistakes include the excessive out-of-plane motion that characterizes the bending motion of the fingers of grippers that employ flexure joints. Such an out-of-plane motion significantly deteriorates the grasping performance during the execution of precision grasps (also called as fingertip or pinch grasps).

The fact that the students are informed and learn from the mistakes of past students, is also evident in the average success rate evolution over the years that is presented in Table I. The success rates of the developed grippers / hands for grasping a range of everyday life objects are presented in Table II. The average scores reported in Table I have been improved by 12.89% from 2017 to 2018, 1.46% from 2018 to 2019, and 14.61% from 2019 to 2020 despite the impact of the COVID-19 pandemic.

B. Overall Results and Student Feedback

The results reveal that the students have prepared over the years a series of robotic grippers / hands that have been impressively successful at executing the tasks of the designed Robotic Grasping and Manipulation Competition. In addition, students have been involved in an experimental design optimization process, showing a particular interest in continuing optimizing their designs even beyond the scope of the assignment (e.g., some students requested access to the 3D printers after the end of the semester in order to test some new ideas). The results illustrate that students genuinely enjoy the opportunity to fully develop a complete biomechatronic device and the design flexibility and freedom that this assignment offers them.

Student satisfaction is evident from the following representative comments that we have received through the SET evaluations and from the feedback that the students have provided through the comments section of the Peer Assessment form:

- "The project was both an intellectually stimulating and challenging project, while remaining comparatively fun to other projects that took place this year."
- "The research project was really helpful as it was very practical and allowed the theory learnt to be used in a meaningful manner."
- "Overall, I think this project was the most enjoyable project I did during my degree."
- "As a biomedical engineer it was an incredible opportunity to integrate physiology and mechatronic systems in a more applicable way. The information provided during the lectures was relevant, given at the right time and incredibly helpful for us to be able to integrate these features into our design. The demonstration session provided extremely useful feedback on the functionality of the gripper and was far enough before the final demonstration day to allow for design alterations. I like that the overall project involves a report, demo, presentation and video as this helps improve a broader range of skills."
- "The grasping and manipulation challenge was an amazing example to apply the concepts we learnt in class to a proper real world setting."
- "Being able to apply concepts by making a hand based on them. Very rewarding."
- "The project, although time consuming and difficult, was actually very helpful for our learning."
- "This project was a huge learning experience and was really fun. Definitely the best project out of all my courses in this degree."

C. SET Evaluations

The feedback that students provide through the Summative Evaluation Tool (SET) surveys has been used to further improve the proposed assignment. The SET scores of the course (Overall Satisfaction) have been improved to 4.55/5 in 2018, 4.68/5 in 2019, and 4.81/5 in 2020. Moreover, in 2018 and in 2020, Minas Liarokapis received a top teacher, students' choice award being recognized as one of the top 15 lecturers of the Faculty of Engineering of the University of Auckland (among 200+ academics).

VI. Discussion and Resources

A. Connecting Theory with the Project Implementation

A good practice is to connect the lectures that discuss the theory behind the project with the actual implementation of the devices. Topics like bioinspiration and biomimetism, actuation systems, and transmission systems can be easily connected to the design and development of the robotic grippers / hands. The lectures should emphasize on how the theory is related to the design and development of grippers / hands for the grasping and manipulation competition.

B. Discussing Design Questions in the Class

Another good practice is all design-related questions to be answered through the first slides of each lecture, providing constructive feedback on the limitations of the designs that the students submit for feedback. Students tend to make similar mistakes and this helps them improve their designs in a collective and synergistic manner.

C. Adequate Practice Time

The students should experiment with their grippers / hands to better evaluate their capabilities, and improve the prototypes through design iterations. The time that the students spend on executing grasping and manipulation experiments with their devices helps them to better understand the theory discussed during the lectures as well as the physical meaning of the concepts taught.

D. Supplementary Materials and Resources

Supplementary materials and further resources that could support the development of similar "hands-on" assignments can be found at the following URL:

http://www.newdexterity.org/rgmc

VII. Conclusion

This paper focused on how a robotic gripper / hand design and development project and the introduction of a grasping and manipulation competition as a course assignment, can significantly increase the student engagement and their understanding of the taught concepts in Robotics and Biomechatronics oriented Engineering courses. A series of best practices have been presented that were trialed over the last four years in two different courses (one undergraduate and one postgraduate) of the Department of Mechanical Engineering at the University of Auckland in New Zealand. The proposed assignment called "Biomechatronics Research Project" asks the students to fully develop a robotic gripper or hand using a single actuator and the required power electronics. The performance of the developed devices is assessed via a Grasping and Manipulation Competition in which the students participate. This paper presents all the components and the details of the assignment, hoping that it could be of help for other lecturers and teachers so as to prepare similar activities. The results of the SET evaluations indicate that such activities help the students better understand the theory discussed during the lectures and increases their engagement and their sense of ownership of the project outcomes.

Future work will focus on extending the grasping and manipulation competition so as to consider challenging environments (e.g., underwater or aerial grasping). Such environments impose additional constraints on the design and performance of the gripper.

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