Multidisciplinary Design Optimization of Robotic Football Players by Undergraduate Students from Multiple Science and Engineering Programs

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Abstract

This paper presents the multidisciplinary design optimization (MDO) and fabrication of four robotic football players: quarterback, center, and two receivers. Each robot has a footprint of up to 16 square inches and is up to 24 inches high. The game of American football is played in an enclosed arena similar to a basketball court and each robot is remotely controlled. The design, fabrication, and operation of the robots involves Indiana University-Purdue University Indianapolis (IUPUI) undergraduates majoring in STEM disciplines, including mechanical, electrical, and computer engineering. The students are exposed to numerous engineering design challenges, such as shock absorbent structure design, fast and dexterous robot maneuvering, development of robust and reliable control hardware and software, and ball transfer between robots in a highly unpredictable game environment. To address these challenges, we adopted a collaborative optimization (CO) approach. CO is a multi-level MDO method that incorporates system-level and subsystem-level optimization. Five disciplines emerged in the course of this project, namely: structures, mechanisms, electronics, software, and manufacturing. CO's advantage over other MDO methods is that it allows disciplinary autonomy while achieving interdisciplinary compatibility. The effectiveness of this experience is demonstrated with the multidisciplinary design, fabrication, and operation of the IUPUI-Butler robotic football team in a game environment.

Introduction

Indiana University-Purdue University Indianapolis (IUPUI) was invited to participate in the 2013 intercollegiate mechatronic football competition organized by the University of Notre Dame. IUPUI was scheduled to play Indiana University-Purdue University Fort Wayne (IPFW) at the end of the spring semester. The goal was to design and manufacture four remotely controlled robotic football players (quarterback, center, and two receivers) in about 20 weeks. At the game day, the robotic football team was completed with Notre Dame robotic players with a kicker and linemen. The design and manufacturing project was carried out by a group of 25 IUPUI undergraduate students (from freshmen to senior) from three different disciplines: mechanical (eleven students), electrical (eight students), and computer engineering (six students). In our work, this challenge is systematically addressed following a multidisciplinary design optimization (MDO) strategy[1].

MDO can be described as collection of design theories, computational tools, and practices developed in the applied mathematical community to improve the design process of engineering complex systems through the interaction of coupled discipline analyses[2]. Its theory was formalized in the aerospace industry where designers recognized the need to decompose a system-level problem into a set of smaller tractable disciplinary problems[3]. Depending on the level of complexity, an MDO problem may involve a large number of analysis and design variables and conflicting multidisciplinary requirements. The discipline coupling forces discipline interaction to arrive to a consistent system design.

This work groups five disciplinary teams: (i) structures, (ii) mechanisms, (iii) electronics, (iv) software, and (v) manufacturing. Depending on preference, expertise, and availability, students are assigned to one or more disciplinary teams. Each disciplinary team has a leader that interacts with the system-level project coordinator to define local objective targets, e.g., speed, weight, range. In order to integrate the disciplinary optimization problems in a system-level platform, this work incorporates a collaborative optimization (CO) strategy[4]. CO allows the work in parallel of disciplinary teams in a way that the system-level problem has control over all the disciplines[5]. The resulting designs are manufactured and used in the game.

Learning outcomes

The students at IUPUI gain exposure to systems engineering. Examples of skills that begin to develop within the members include project management practice for team leaders and discipline design decisions that impact adjacent disciplines for all team members. For example, the team designing the circuitry are able to employ the theory and analysis skills learned in their circuit's class. Likewise, the team designing the linkage are able to employ the machinery design analysis tools learned in their respective class. The complexity of learning systems engineering in its entirety is not realistic given the format of the student club, however student learning is achieved through practice. Student learning include the following objectives; 1) team work and building effective meeting skills where tasks are clearly identified and assigned, 2) cross discipline involvement, 3) learn how to design, build, and test robots using knowledge gained from past/present courses, and 4) communication skills. Student learning is motivated by participation of the robotic football competition given the robots are functional. The students will be able to demonstrate the learning accomplishment by participating in the next football competition April of 2014.

Design guidelines

The game is played on a 94 ft × 50 ft field by two robotic teams identified as Blue and Gold (Figure 1). Each team is composed of a total of nine remotely controlled robotic players, but no more than eight are allowed on the playing field during a play; six robots were actually used by each team during the 2013 game. The game commissioners provide a miniature souvenir football for the game. In the 2013 scoring, a field goal is worth 3 points, a touchdown is worth 6 points, a kicked point after touchdown is worth 1 point, a short forward pass (5 to 15 feet) is worth 7 points, and a long forward pass (more than 15 feet) is worth 12 points! There is a 3-point penalty if the ball is damaged by a robot during the game.

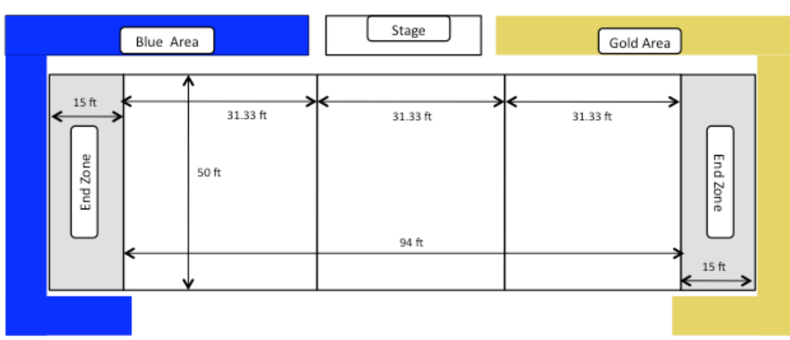

Figure 1—Playing field dimensions. The opposing teams are identified as Blue and Gold. Student players and additional hardware can be located in the designated areas around the field.

All robots are operated by remote control using the controllers provided by the commissioners. If other remote controllers are used, they cannot interfere with the signals broadcast from the opposing team. The robot locomotion must be DC powered with a 24V maximum circuit voltage. Each robot must have a kill-switch mounted externally to their top surface. When activated, the switch should disconnect the main power to the system.

The weight of the each robot (except quarterback and kickers) is limited to 30 pounds. Quarterbacks are limited to 45 pounds. At the beginning of any play, all robotic players (except centers and kickers) must fit within a 16 inch ×16 inch footprint × 24 inch tall box. Centers may reach out from beyond this footprint before a play to deliver the ball to another player. The centerline of a player's base plate must be located 3.0 ±.1 inches above the playing surface and remain in that position at all times. Each robot is required to incorporate a digital accelerometer to sense upsetting events such as knockdown, fall down, or tackle. A single multi-color, high-intensity LED is used to indicate robots status, e.g., red indicates an upsetting event. A student can remove a damaged robot from the field between plays, but once touched by a human, that robot cannot participate in the next play unless the team calls a time out.

Robots other than the center can have up to two extensible arms consisting only of rotational joints. Each arm may extend no more than 18 inches in any direction from the center of the joint at which it connects to the player. However, the 2013 guidelines do not allow the deployment of any material beyond the perimeter of the robot’s base plate that impedes the ability of an opponent to contact a robot’s base plate. The base of each robotic must be solid and made of HDPE not thinner than ½ inch. A reasonable number of clearance holes for component mounts, component clearance, fasteners and wires are allowed. Tires must be mounted on rigid, solid wheels. Pneumatic tires are not allowed and suspensions and shock absorbing systems are not permitted.

MDO approach

In the fall semester of 2012, the project was presented to mechanical engineering undergraduate students of the course Design of Mechanisms (ME 37200). Following this presentation, a group of students from this class funded the IUPUI Robotics Club that later included students from electrical and computer engineering. Twenty-five students were involved in the development of the four robots. Instead of independently assigning the development of each robot to a group of students, say six students per robot, this project incorporated disciplinary teams based on preference, expertise, and availability. In this project, the robotic system is described as a non-hierarchical collection of five disciplines:

- Structures: to design robot chassis and transmission for the robot displacement
- Mechanisms: to design all moving components on the chassis
- Electronics: to design, select, and fabricate electronic boards and peripherals
- Software: to design and program control algorithms
- Manufacturing: to fabricate and assemble final robot

As the project evolves, the inter-disciplinary coupling changes so the design and communication tools should allow such natural evolution. The main challenges faced in this project are the organizational issues related with the data sharing and inter-disciplinary communication. Students quickly learn the need to coordinate the activities of a multidisciplinary team and keep everyone on board required the use of a systematic MDO approach such as collaborative optimization.

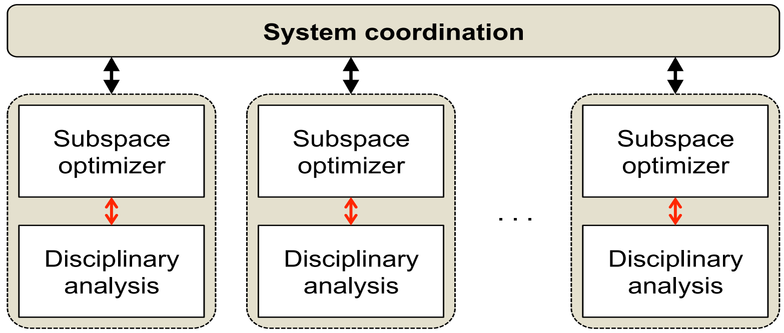

Figure 2—Collaborative optimization (CO) framework.

Collaborative optimization is a bi-level design framework composed of system-level and discipline-level design problems (Figure 2). In CO, individual disciplinary teams are in charge of solving local optimization problems by varying local design variables. Since each discipline only deals with a sub-space of the design problem, it may not be possible to obtain a local feasible solution. For example, the mechanisms team does deal with the actuator control of the electric boards team; therefore, the sole design of the ball transfer mechanism may not satisfy constraints imposed on the ball trajectory. Thus, it is the job of the disciplinary team to minimize deviation from the targets imposed by the system-level while working to define a design that can be accepted by all the other disciplines. In turn, the system-level coordination adjusts the target values such that a feasible design can be obtained by all the disciplines. An example of how the students learn the positive impact of the CO process can be seen in the selection of the linkage actuator which falls on the interface between three disciplines; mechanisms, electronics, and software. The mechanisms discipline has targets on the torque requirement, electronics has limits to the voltage available, and software has protocol feasibility constraints. The three disciplines cannot all achieve the targets they individually desire. The students, according to the CO approach, must adjust the constraints of each discipline to select an actuator that acceptable to all local problems. Students learn the basic tools that are essential when entering a professional industry. The tools learned include data sharing and inter-disciplinary communication with web-based tools such as Indiana University's OnCourse that contains a repository for electronic documents (including individual Drop Box), mail communication, calendar, and a Wiki tool (https://oncourse.iu.edu/).

Figure 3—Cardboard prototype of the spinning-wheels baseball launcher

Design optimization process

To illustrate the design approach, let us consider the design of the quarterback. During the game, the quarterback has three independent missions: passing the football, handing off the football, and running the football on its own. Based on the game scoring, the most important mission is passing the football (long and short forward pass); therefore, special attention is given to the football throwing mechanism.

After considering football-launching approaches including pressured air cannon, spring launcher, and spinning-wheels ball launcher, the latter alternative is selected due to the fewer components, power efficiency, reduced volume, and the ability to more easily control the football distance during the game. Furthermore, this is a proven alternative in tennis and baseball launching machines. Figure 3 shows a prototype made of cardboard. The launching angle is fixed at 45° so the football's distance is maximized for the given wheel spin angular velocity. The target for the electronic team is the design of the speed controller and the selection of the actuators. The final design are brushed motors, 12VDC nominal, 6 – 14V operating range, 486.2 mN-m stall torque, 62.4 mN-m peak efficiency, and 85A stall current, 10.9A peak efficiency. The motors are coupled to a planetary gearbox with reduction ratio of 4:1. Drive and shooter wheel speed is controlled using Talon speed controllers, which are based on locked antiphase rectification to vary the power per time delivered to the motors. This allows current to travel back to the power source when not used.

The follow up problem consists on the design of a linkage to move the football from the initial position in which is received to the final position at 45° between the spinning wheels (Figure 4). The mechanism discipline problem is stated as follows:

$$
\begin{aligned}
&\text{find} && \boldsymbol{x} = [\boldsymbol{O}_{12}, \boldsymbol{O}_{14}, r_3] \\
&\text{minimize} && f(\boldsymbol{x}) = \max\left\{\left|\frac{\pi}{2} - \mu_{\max}(\boldsymbol{r})\right|, \left|\frac{\pi}{2} - \mu_{\min}(\boldsymbol{r})\right|\right\} + \exp(F(\boldsymbol{r}) - n) \\
&\text{subject to} && \boldsymbol{r}_1 + \boldsymbol{r}_2 = \boldsymbol{r}_3 + \boldsymbol{r}_4 \\
& && r_1 + r_2 + r_3 + r_4 \leq 800 \text{ mm} \\
& && 0 \leq O_{12x} \leq 400 \text{ mm}, \qquad -60 \text{ mm} \leq O_{12y} \leq 10 \text{ mm} \\
& && 0 \leq O_{14x} \leq 400 \text{ mm}, \qquad -60 \text{ mm} \leq O_{14y} \leq 10 \text{ mm} \\
& && 100 \text{ mm} \leq r_1 \leq 400 \text{ mm}, \qquad 70 \text{ mm} \leq r_3 \leq 170 \text{ mm} \\
&\text{where} && \mu_{\min,\max}(\boldsymbol{r}) = \operatorname{acos}\left[\frac{r_4^2 - (r_1 \pm r_2)^2 + r_3^2}{2 r_4 r_3}\right] \\
& && F(\boldsymbol{r}) = \max\left\{\frac{r_1}{r_2}, \frac{r_3}{r_2}, \frac{r_4}{r_2}\right\} \\
&\text{and} && \boldsymbol{r}_i = r_i \begin{bmatrix}\cos\theta_1 \\ \sin\theta_i\end{bmatrix}, i = 1, \ldots, 4
\end{aligned}
$$

where $\boldsymbol{O}_{12}$ and $\boldsymbol{O}_{14}$ are the coordinates of the fixed poles. The disciplinary analysis is performed in Matlab using an in-house code for four-bar linkage analysis. The subspace optimizer is Non-dominated Sorting Genetic Algorithm II (NSGAII) available in VR&D VisualDOC. The optimal design is

$$\boldsymbol{O}_{12} = \begin{bmatrix}266.6 \\ 6.7\end{bmatrix} \text{mm}, \qquad \boldsymbol{O}_{14} = \begin{bmatrix}344.2 \\ -53.7\end{bmatrix} \text{mm}, \qquad r_3 = 159.0 \text{ mm}.$$

Given the inertial loads of the linkages and approximated performance targets, the electric actuators are 12 – 16VDC operating voltage, 28.3 kgf-cm stall torque @ 12V, 0.26 degree resolution. The control includes position feedback and the gearbox contains metal internal gears.

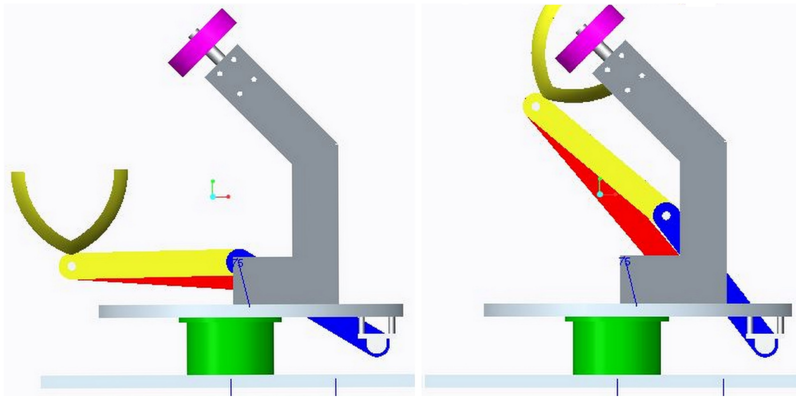

Figure 4—Design of the football positioning mechanism from initial to the launching positions

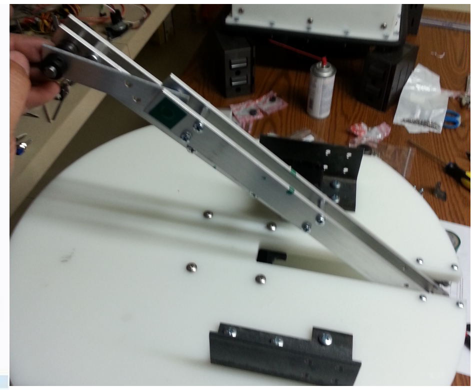

Figure 5—Fabricated positioning linkage in Aluminum

Support and transmission design

Robot locomotion powered by two rear driven wheels enables forward left right and reverse motion. Modulation of either left or right wheel speed causes left or right robot motion. Conversely, equal left and right wheel speed results in straight robot motion. The front wheel is a three-degree of freedom spherical caster wheel. The final design employs brushed 12VDC motors and 16:1 ratio gearboxes. A 12V battery powers all five Talon motor controllers as well as the Dynamixel RX28 four bar mechanism actuator and a 9V batter powers the Arduino. PWM wiring between the Arduino and Talon speed controllers is achieved via standard three wire, three pin (0.1”/2.54mm pitch) connectors of various lengths and male/female ends. Wiring to and from the 12V battery is achieved via solid copper 24AWG with appropriate terminal connectors at each end. Bulk wire and terminal connectors were purchased so each connection could be custom. The main battery is a 12V, 7.2Ah, lead acid rechargeable battery while the 9V Arduino battery is a standard alkaline disposable unit. Control subsystem is composed of an Arduino Mega 2560 microcontroller which handles the processing of the input commands received from the remote control. Target control functions include processing the following inputs:

- Drive joystick position from one channel to output forward and reverse motor speed.
- Turn joystick position from one channel to output the left and right motor speed.
- Shooter wheel speed joystick position from one channel to output shooter motor speed.
- Shooter turn table joystick position from one channel to output motor speed and direction.
- Trigger signal from one channel to activate a control cycle in which the four-bar actuator turns to a position and returns back to initial position.

There are two parts to the control subsystem, the hardware and the software. The software to process all five functions listed above is programmed using the Arduino 1.0.5 interface and loaded on the Arduino Mega 2560 microcontroller. Communication between Arduino and the Talon controller is achieved via the pulse-width modulation technique where duty cycle modulation results in a modulation of motor speed. Communication between Arduino and the Robotis Dynamixel RX28 actuator is not as simple. The RX28 actuator communicates in RS-485 protocol, which requires a translator transceiver chip to translate the Arduino serial signals. On April 20, 2013, the four robots competed at IUPUI joined Notre Dame’s gold while IPFW robots joined Notre Dame's blue team. The final score was 17 – 16 in favor of the gold team. The final robots are shown in Figure 6.

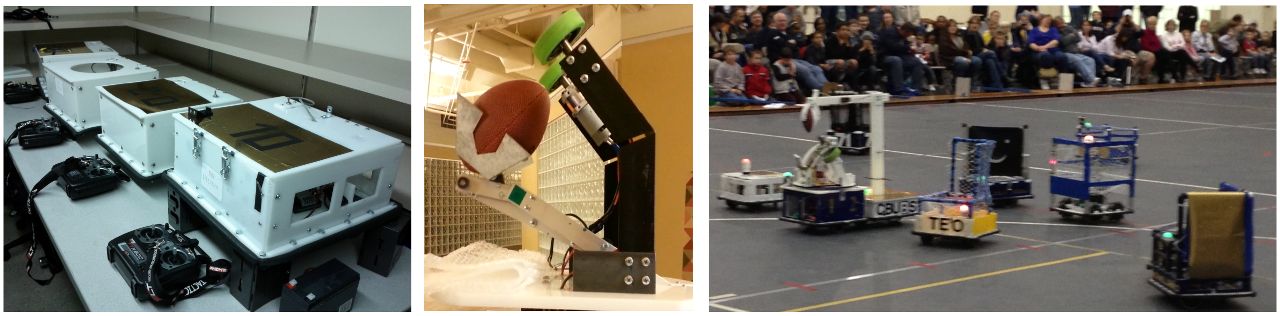

Figure 6—Left: support and transmission module for the four robots. Center: Final robotic quarterback. Right: IUPUI and Notre Dame Gold team vs IPFW and Notre Dame Blue team.

Learning Assessment

A survey was conducted to 23 students to assess their experience in the project. The survey asked students to rate each statement on a scale of 0 to 5, 0 equating to strongly disagree and 5 equating to strongly agree. The following questions were asked:

- Participating in the IUPUI Robotics Club allowed me to utilize the knowledge gained from my engineering classes.
- Participating in the IUPUI Robotics Club allowed me to improve my communication skills.
- Participating in the IUPUI Robotics Club improved my team working skills.

The results of the survey show that 82% of the students were able to apply the engineering material covered in prior classes. 75% of the students believed their communication skills improved and 89% of the students agreed that their team working skills have improved. It is expected for communication to be rocky given the environment of the Club. The Club maintained two web based locations where material and communication was exchanged. It is the author's belief that if all communication were to be condensed to one space (such as a wiki space) there would only be one possible location to find information. It was pleasant to find that most of the students were able to improve team working skills. Team work is a must in any engineering industry.

Final remarks

This paper presents the design process of four robotic football players (quarterback, center, and two receivers) by undergraduate students from mechanical, electrical, and computer engineering. The project is systematically addressed with a CO strategy, which allows disciplinary autonomy while achieving interdisciplinary compatibility. Following this strategy, a system-level coordinator assigns targets to five disciplinary teams: structures, mechanisms, electronics, software, and manufacturing. Each disciplinary analysis makes use of an optimizer. The paper illustrates the design of a football positioning linkage for the shooter mechanism in a robotic quarterback. This process involves Matlab simulation using an in-house code with VisualDOC NSGAII. A similar approach is applied to other disciplinary problems obtaining a feasible system design. However, the use of subspace optimizers is only possible when a simulation model is available. Simulation models were mastered by some of the mechanical engineering students, which made the application of CO straightforward for the mechanisms disciplinary team. Other predictive models are based on worst-case scenario analysis and factor of safety analysis. Further, the use of optimization methods is not commonly used in undergraduate curricula, which could have created an additional challenge for the group of students who coordinate the project. Team work, effective meeting skills, and cross discipline involvement introduces the some of the concepts in systems engineering which allows students to gain an advantage in the marketplace.

Future work is to explore state of the art MDO methodologies and apply one to a second generation of football playing robots. This task will be accomplished with the use of appropriate predictive tools for each disciplinary team. Structural optimization methods and uncertainty quantification may be incorporated[6]. Our vision for a second generation of robots would feature intelligent mechanical systems which perceive the environment, reason, make decisions based on perception, and act accordingly.

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