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Design of an Autonomous Pace Car for Athletic Training: a Multidisciplinary Undergraduate Research Experience

Mr. Martin Fevre, Elizabethtown College

Martin Fevre is an undergraduate student currently pursuing his B.S. in Engineering with a concentration in Mechanical Engineering at Elizabethtown College. During his first three years at Elizabethtown College, he has found that he is adept at building analytical models with software such as MATLAB, like he did in his Numerical Methods course. Beside his undergraduate research, Martin started a group project featuring a quadrotor helicopter that aims to map out the interior of a building to assist blind students. Martin's post-graduate research interests include aerospace, aeronautics, robotics, and automation.

Dr. Tomas Estrada, Elizabethtown College

Dr. Tomas Estrada is an Assistant Professor in the Department of Engineering and Physics at Elizabethtown College, in Elizabethtown, PA. He received his B.S. in Electrical Engineering from Universidad de Costa Rica in 2002 and his M.S. and Ph.D. (both in Electrical Engineering) from the University of Notre Dame in 2005 and 2009, respectively. His research interests include control systems, engineering education, technology-related entrepreneurship, and sustainable engineering applications.

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Introduction

Over the past three decades, major advances have been made relevant to automation, and technological expectations have increased in order to correct human error. Some of the most groundbreaking advances in automation can be found at the junction of mechanical engineering, electrical engineering, and computer science. These three disciplines, when applied together, are known as mechatronics. For example, two important applications of mechatronics automation are the growing interest in autonomous cars and the development of health care devices[1,2]. In the field of athletic training, however, there have been limited improvements[3], and the opportunities remain vast. The purpose of this paper is two-fold: first, to present an example of mechatronics applied to athletic training, and, secondly, to share a unique undergraduate multidisciplinary engineering research experience in a small liberal arts college setting.

The research team was multidisciplinary in nature since it was composed of an undergraduate student, midway through a general engineering program with a concentration in mechanical engineering at a small liberal arts college, and a professor in electrical engineering. The research project itself was multidisciplinary as well since it combined mechanical engineering, electrical engineering, and computer science into the design of a pace car intended to assist a runner during his athletic training. In terms of technical goals, the car needed to follow any type of line on indoor and outdoor tracks and perform different workouts, such as steady-state runs or interval training. To situate the line on the track, the research team used infrared reflective phototransistors to design sensing and control algorithms. An Arduino microcontroller was used to interact with the sensors, manage the electronics, and encode a Proportional-Integral-Derivative (PID) controller[4].

This research experience was a unique opportunity for the student during the summer before his junior year. In a small liberal arts college setting, the student had fewer resources available than he would have at a larger research university, but benefited from a very close interaction with his advisor. Furthermore, using the *Informed Design Teaching and Learning Matrix*[5] as a framework, an evaluation was performed before and after the experience to monitor the evolution of the student as a researcher. The student, who was used to traditional course-based learning, manifested remarkable ability to progress and learn in a research-based environment. After the conclusion of the research experience, the student showed growing interest in continuing to perform mechatronics research at the graduate level.

The rest of the paper is organized as follows: in Part I, we begin by addressing the project set-up, educational goals, challenges and opportunities. In Part II, we then move on to a closer look at the technical design of the project. Finally, in Part III, we revisit the educational goals set out at the outset, make a reflective assessment of the experience, and propose insights and recommendations for instructors working with similar experiences or sets of challenges.

Part I: Educational Goals, Challenges, and Opportunities

Before diving more deeply into reviewing the educational goals, it would be important to explore the background of the institution and other contextual matters that scaffolded the experience.

The project was housed in the Department of Engineering and Physics at Elizabethtown College, in southeastern Pennsylvania. Elizabethtown College is a small liberal arts college (<2,000 students), and the department offers ABET-accredited programs in general engineering program with multiple concentrations (electrical, mechanical, applied physics) as well as in computer engineering. The department currently consists of 8 full time faculty, and there are roughly 140 students in the major.

The program places a strong emphasis in maintaining a project-oriented curriculum throughout all four years. Students start working on projects during their Introduction to Engineering sequence in the first year, continue through Sophomore Project and Junior Design, and culminate in a two-semester capstone Senior Project course. However, particularly motivated students can pursue additional design and research experiences by seeking out a faculty member and proposing a project, which may consist of either a novel, student-generated concept or a further development of a pre-existing project. These directed research experiences can take place at any point during the student's four years, whether during the academic year or the summer.

In this case, the experience itself took place in a seven-week span during the summer between the sophomore and junior year. Funding for the experience was available through the college's summer Scholarship and Creative Arts Research Program (SCARP). As mentioned in the Introduction, both the project itself and the research team were multidisciplinary in nature. The team was composed of an undergraduate student, midway through a general engineering program with a concentration in mechanical engineering, and a professor in electrical engineering. The project was a second-stage of development for an idea originally developed for a Senior Capstone project. The research group for the capstone project consisted of four students of various engineering concentrations, who ultimately presented their work at a regional conference[6].

With the above context in mind, the instructor set out to design a research experience that would be challenging and rewarding for the student. In the continuum of process vs product-oriented undergraduate research, the emphasis was on the process-side, with student development being the main goal. The summer research experience was thus crafted with several key features in mind:

-The project needed to be *multidisciplinary in nature*, involving concepts and skills from various engineering-related disciplines, such as electrical engineering, mechanical engineering, and computer science.

-Both in terms of content and skills required, the experience should include material *beyond what student had seen so far in his coursework.*

-The experience should *foment independence* in the student.

-The process itself should be *challenging from a technical standpoint*.

-Perhaps most importantly, the experience should provide the student with development opportunities through *varied forms of learning*.

To develop this last point further, the instructor and student set-out to collaboratively craft a research experience that would allow the student to engage in the following:

- Learning by doing
- Learning by brainstorming and prototyping
- Learning from iteration, feedback, and failure
- Learning by noticing and troubleshooting
- Learning by dialoging with people
- Learning from reflection

In Part III we will revisit this list with a more detailed description of the tasks that contributed to learning in each of these dimensions.

<u>Challenges and Opportunities</u>

Bearing the context described earlier in mind, we acknowledge that the team confronted a variety of challenges, many of which are common to faculty and students seeking to pursue research or design endeavors in a small college. We now provide a more detailed explanation of the challenges of the experience, explaining how they applied to this case in particular:

-*Small college facilities:* Compared to large research universities, the laboratory space, equipment, and other resources were quite limited.
-*Limited budget:* In line with the above, financial resources were modest as well.
-*Multidisciplinary team and project:* With a professor of electrical engineering mentoring a student with a mechanical engineering concentration, both student and instructor would need to branch out beyond their comfort zone to tackle the challenges that would arise throughout the project.
-*Incorporating topics of interest which may not be in the curriculum:* The unique focus of the project necessitated that the student become acquainted with new material not previously covered in his coursework.

As mentioned at the outset, the general strategy when dealing with these limitations is to turn each challenge into an opportunity. With this mindset, we identified the following set of opportunities:

-The small college facilities and limited budget could increase students' motivation to seek clever engineering solutions rather than buying a more expensive piece of equipment.
-Working in a multidisciplinary project could lead to student growth, increased communication skills, and increased abilities at fields of study outside his own concentration, while at the same time allowing professional growth for the faculty member.
-Finally, having to expand beyond what the student had previously learned in the classroom, the student could develop a more tangible sense of how the theoretical material from the coursework may lead to practical solutions in engineering applications.

In addition to the above opportunities, there were unique characteristics of the setting (undergraduate research project in a liberal arts college) that could lead to intrinsic advantages. For example:

-*Absence of graduate students:* Because the instructors did not also direct graduate-level research, all project-oriented time is devoted to undergraduate students, thereby allowing a closer level of mentorship.
-*Cultural dimensions of student-faculty interaction:* The culture in this college (as is the case in many small liberal arts colleges) is one where students are encouraged to reach out to faculty whenever they need guidance. In research-driven institutions, such interactions may be more intimidating for an undergraduate student.

In order to assess the effectiveness of the research experience, particularly relative to its central goal of fomenting student development in engineering research and design, we used the *Informed Design Teaching and Learning Matrix*[5] as our central framework. The Matrix explores nine different dimensions of student development from "beginning designer" to "informed designer," and provides various tasks that could help the student grow in each of these dimensions. In Part III we explore the Matrix's dimensions and assess the effectiveness of the tasks of this research experience in each of those dimensions. Before we can do that, however, let us first explore the technical design in more detail.

Part II: Technical Design

Strategy to Improve the Functionality of the Pace Car

Working alone on a multi-facet project, the student had ample freedom to choose what aspects of the car he wanted to improve, while covering the main technical objective of the research experience, which was to improve the general functionality of the car. The first day of research was dedicated to the elaboration of a "wish list," as well as the planning of the 7-week experience. The student was free to include any ideas he ideally wanted to cover or implement. This list was then reviewed and arranged in order of importance by the faculty advisor and the undergraduate student. Being relatively new to programming on Arduino and with the concept of control and signal processing, the student started the experience by tackling multiple easy individual tasks in order to get more familiar with the material involved in this mechatronic project. The initial wish list included such tasks as adding LEDs to the car to provide visual checks to the user; creating a smartphone application for wireless user input; implementing a keypad for user input; creating different workout programs; adding speakers to give audio representations to the user before, during, and after the run; replacing the sensors that return anomalous values; implementing small-sized solar panels on the car to recharge the battery continuously; and obviously, increasing the speed of the run.

Before the summer research, the pace car was able to follow a white line on a black surface at very low speed for a short period of time, before overshooting the curve trajectory and losing track of the line. In order to diagnose and troubleshoot the difficulties and problems faced by the pace car, a strategic plan to test and improve the steering control was established. This plan consisted of running the car for basic cases first, and then, gradually tackling more challenging empirical cases, with the simplest case being the white line on black surface. On the other hand, empirical cases could be manifold: colored lines on the gym floor, white line on red surface on the outdoor athletic track, or even extra lines and objects interfering with the trajectory of the car. Three major steps were therefore considered: basic case, basic empirical cases, and empirical complications. The student was initiated to experimental PID tuning after the second phase of the plan. This strategy is illustrated in the table below.

Table 1. Strategic Plan to Improve Steering Control

ORDER OF DIFFICULTY ↓

Step	Case of Operation	Description
①	Basic case	Lab conditions: black vs. White
②	Basic empirical cases	Gym floor: colored lines Athletic track: white vs. Red
	PID tuning	
③	Empirical complications	Extra lines Parasite objects (stones, leaves)

Sensing

Using a 3D printer, the former students created a sensor bar and mounted it to the bumper of the car. Infrared reflective phototransistors were chosen to detect the line on the athletic track[7]. Five IR sensors were originally used by the first prototype to detect the position of the car with respect to the line. Later on, the research team decided to increase the number of sensors to 16 to provide more accurate feedbacks on the position of the car. The sensors were evenly spaced at intervals of 9.525 mm on the bar. Each sensor emits an infrared light off the floor and returns a voltage that varies with the color and darkness of the surface. With 16 analog pins, an Arduino Mega 2560 microcontroller was used to process the voltages read by all 16 sensors.

In order to correct the trajectory of the car, it was necessary to develop an algorithm of sensor fusion[8,9]. This algorithm is illustrated in Figure 1.

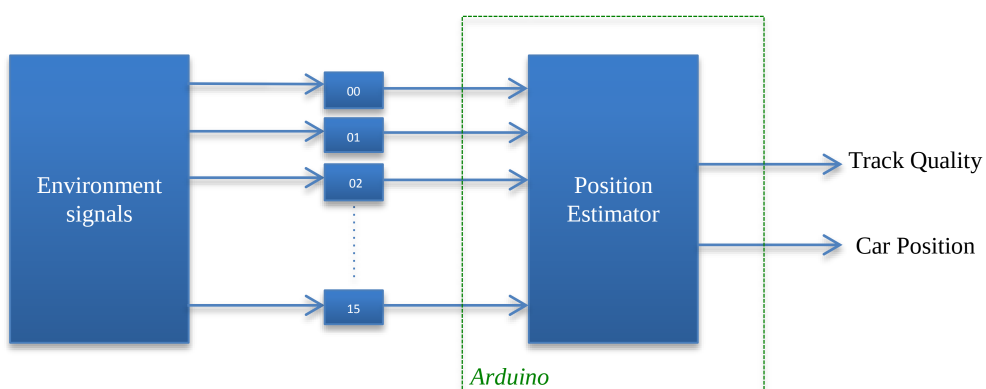


Figure 1. Sensor Fusion Process

After gathering information from every sensor, it was then necessary to numerically estimate the position of the car with respect to the line. Using all the sensors, a single error value must be calculated to determine whether or not the car is well-centered on the line. The research team, firstly, needed to set a threshold value to separate the line values and the values of the surface around it. Secondly, each sensor was given an initial angle depending on its location on the sensor bar. Sensors 7 and 8 were each assigned an initial angle of 90 degrees, designated as the middle of the sensor bar. Moving left from the middle of the sensor bar, each sensor was assigned an angle, from 90 degrees for sensor 7 in the center, and decreasing by 10 degrees, to 30 degrees for sensor 0. Symmetrically, sensors 8 to 15 were each assigned angle values on the right, varying from 90 degrees at the center, and increasing by 10 degrees, to 150 degrees for sensor 15. Based on the value of each sensor compared to the threshold, the Arduino microcontroller computes a weighted average angle for the sensor bar, which will be the error signal and input of the PID controller. The PID controller aims to minimize this error by making the car steer back to the center of the line.

Self-Calibration of the Sensor Array

A major breakthrough that enabled the progress of the algorithm of trajectory control and, therefore, the overall functionality of the pace car, was the self-calibration of the sensor array. This included a calibration of the sensors as well as a self-calibration sequence for the vehicle, which was run upon initialization of a trial[10].

The research team observed trends of some sensors to return higher or lower values than average, which was comprehensible due to the low quality of the cheap sensors. Runs were performed inside the gym to gather readings from different surfaces. The runs were statistically analyzed to calculate individual coefficients for each sensor[11,12]. Runs were performed after implementing each coefficient to its corresponding sensor in the Arduino code. A second statistical analysis, depicted by the tables and graphs below, allowed the team to compare the irregularity of the sensors and the uniformity of the sensor array, respectively before, and after normalization.

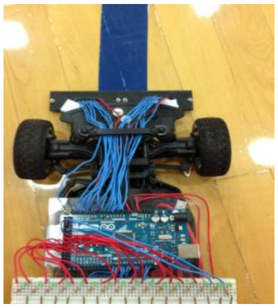


Figure 2. Gym Floor: Dark Blue Line

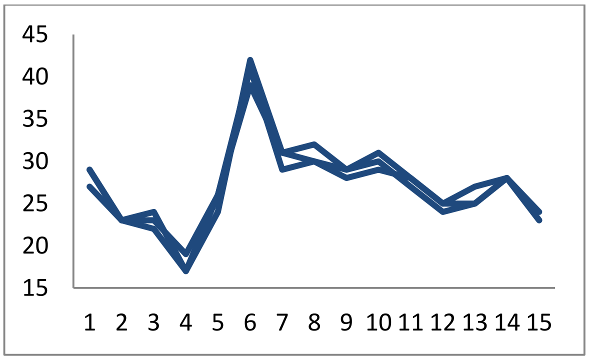


Figure 3. Blue Line Before Calibration

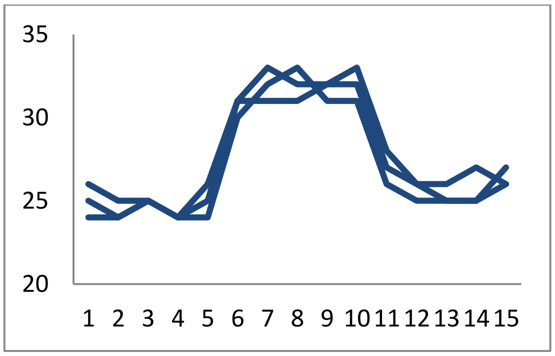


Figure 4. Blue Line After Calibration

The results of the normalization of the sensor array was very positive, since the blue line returned values ranging from 30 to 33 after calibration (pattern observed in Figure 4), against a range from 24 to 42 before calibration (Figure 3). While it is challenging to tell where the line is situated thanks to Figure 3, Figure 4 provides a clear, and therefore reliable information to the microcontroller about the position of the car with respect to the line.

Furthermore, significant differences were observed between the values returned by the black line and the values from the lighter lines. Table 2 in Appendix A shows typical black values and blue values returned by the IR sensors. Hence an algorithm of self-calibration must also be implemented to allow the car to determine the case of operation prior to run. This algorithm is further described in Appendix B.

Speed and Trajectory Control

The vehicle's performance can be evaluated based on two major criteria: its speed, and whether or not it is able to follow the line on a given surface. The main technical goal of the research was to increase the speed of the car, while keeping a smooth and undisturbed trajectory upon the line on an outdoor track.

Speed Control: Open-Loop Control

For this application, some external disturbances, such as wind or hills, could cause the car to run at a different speed than the one requested by the user before the run. Nonetheless, due to the small size of the car and its limited applications, these slight errors were ignored, and the research team opted for an open-loop control methodology for the first prototype of their line following pace car (Appendix C).

Trajectory Control: Feedback-Loop Control

A closed-loop system was indispensable for the proper operation of the trajectory control algorithm. Furthermore, a deviation from the line could cause serious damages to the robot. The reference input that the car must follow is the center of the line. The steering servo plays the role of actuator for the system and assigns mechanical commands to the plant. Mainly constituted by the IR sensors, the feedback loop was designed to estimate the new position of the car after every mechanical response[14]. The algorithm of position estimation mentioned in Section II.C is also part of the feedback loop since it must numerically process the readings from all 16 sensors. Finally, an error signal is assigned to a PID controller corresponding to the difference between the center of the line and the estimated position. The controller must then minimizes the error signal to correct the trajectory of the car.

The functioning of the closed-loop responsible for trajectory control of the pace car is summarized in Figure 8.

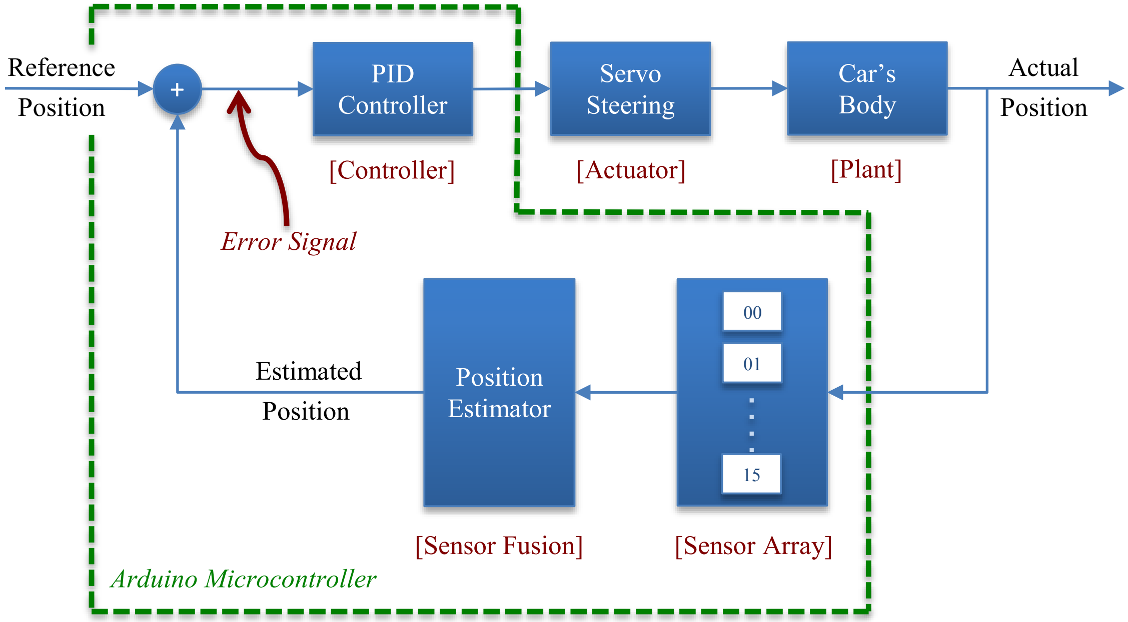


Figure 8. Closed-Loop for Trajectory Control of the Pace Car

A controller was essential to the feedback-loop responsible for trajectory control. The research team opted for a PID controller. The mathematical framework of this controller is explained in Appendix D.

Part III: Educational Assessment, Discussion, and Recommendations

Having looked at the technical design, we can now reflect back on the educational goals outlined in Part I, using the Informed Design Teaching and Learning matrix as the primary framework for assessing the effectiveness of the research experience.

The matrix not only served as an assessment tool, but informed the design of the activities the student conducted through his seven-week experience. As mentioned in Part I, the activities were designed to promote learning in various forms. Upon completion of the project, student and instructor reflectively analyzed the various forms in which learning took place, mapping each to specific activities. The observations are summarized as follows:

- Learning by doing: The project itself was mainly hands-on in nature. While the student learned theoretical material from various sources (textbooks, external online resources, conversations with the advisor), it was in seeking to implement this material into the project that the student experienced most significant growth.
- Learning by brainstorming and prototyping: During the first week, the student created a "wish list" of functionalities of the pace car to be enhanced. During this stage, free, unrestricted brainstorming was encouraged. When the student narrowed the focus of his research, he was encouraged to brainstorm ideas for the various design challenges encountered along the way. Examples of this include the selection of the microcontroller to be used and the control algorithm to be implemented.
- Learning from iteration, feedback, and failure: One of the more surprising things for the student was how, contrary to his previous experiences in his coursework, many of the things

he tried did not go as expected. The student initially expressed frustration and self-doubt, but throughout the seven weeks gained the confidence to be more patient and approach things differently; seeing “failure” as an opportunity for learning and deeper understanding of the system.

- Learning by noticing and troubleshooting: The student crafted equations based on experimental data and had to troubleshoot problems by performing tests to identify which aspects of the car’s functionality were malfunctioning.
- Learning by dialogue: The student had in-depth conversations with the research advisor (who had done previous research in the field of Control Systems) multiple times per week.
- Learning from reflection: In addition to the design tasks, the student was encouraged to watch videos from expert speakers about various topics. The student kept a journal of the videos he watched, making observations both on the topics and on the delivery by the speaker, with the intent of implementing the habits of expert speakers into his own presentations. Furthermore, the student and instructor would periodically “take a step back” to reflect on the progress of the research, what had been going well, and what needed to be changed. The student performed a thorough self-examination of his research progress after the seven weeks.

In line with the idea of learning for reflection, the student considered his growth in each of the dimensions of the informed designer matrix. The results are summarized in the following table:

<u>Table 4.</u> Student Self-Assessment

Design strategies	Beginning vs. Informed Designer Patterns	
	Beginning Designers	**Informed Designers**
Understand the challenge	**A.** Problem solving vs. problem framing	
	1	7
Build knowledge	**B.** Skipping vs. doing research	
		1 7
Generate ideas	**C.** Idea scarcity vs. idea fluency	
	1	7
Represent ideas	**D.** Surface vs. deep modeling	
	1-	-7
Weight options & make decisions	**E.** Ignore vs. balance benefits & tradeoffs	
	1-	-7
Conduct experiments	**F.** Confounded vs. valid experiments & tests	
		1 7
Troubleshoot	**G.** Unfocused vs. diagnostic troubleshooting	
	1	7
Revise/Iterate	**H.** Linear vs. iterative designing	
	1	7
Reflect on process	**I.** Tacit vs. reflective design thinking	
	1	7

1: student's self-evaluation before the research experience
7: student's self-evaluation after 7 weeks of research
1--7: in between the two profiles

Each of the categories listed on the above table are framed by the dimensions listed in the *Informed Design Teaching and Learning matrix*, with the major goal of the research experience to help the student move from “beginning designer” to “informed designer.” Throughout the process, the student was encouraged to take productive risks while working with creative ideas. The matrix dimensions informed the selection of the research activities and served as a lens under which to study the development of the student. We now consider these dimensions more closely.

A. Problem framing vs Problem solving
The student made very significant progress in this dimension. As an example, during the first week, the student coded a 1000-line script thinking the steering algorithm would be simple. Needless to say, the resulting script was ineffective. Later, the student avoided making such early design decisions, at least until all the facets of the challenge had been explored. By contrast, during the fourth week, the student developed a systematic testing plan for the vehicle. Establishing a testing plan reduced the amount of redesign work needed to accommodate unanticipated changes.

B. Skipping vs Doing Research
Exhorted to this effect by the instructor, the student made sure to conduct research before diving into changes for the hardware and software of the pace car. For example, due in part to the limited budget for the project, the student performed thorough online research before purchasing any new parts.

C. Idea Scarcity vs Idea Fluency
The seven-week experience started off with an emphasis on ideation-focused tasks, such as developing a wish list for new features to be added to the car. The student then grouped, organized, and prioritized these ideas to enhance his ability at ideation and aiding in the overall design process. The student also read articles from technical engineering magazines and watched online videos on various academic topics to expose him to a broader understanding of today’s technological challenges and opportunities.

D. Surface vs Deep Modeling
The student followed a systematic process in modeling the functionality of the pace car, starting from a simple drawing, and then proceeding to a more detailed drawing and the development of a prototype. Following various iterations according to necessary changes, the student can then continue to a final CAD drawing of the vehicle and construction of the final product. At the end of the seven weeks, the product is at the prototype stage.

E. Ignore vs. Balance Benefits and Trade-offs
Thanks in part to his previous experience in courses such as Introduction to Engineering, the student was familiar with techniques such as Pugh Tables, which allowed him to incorporate benefits and trade-offs into his decision-making process.

F. Confounded vs Valid Tests and Experiments

The student changed only one variable at a time when conducting experiments. He performed several changes to the hardware and software of the vehicle to ensure proper testing. For example, he calibrated each sensor to make the readings more accurate by running a large number of tests and then adjusting the sensor coefficients based on the data from the tests. His process for tuning the PID controller also displayed a deliberate strategy for testing and experimenting.

G. Unfocused vs Focused Troubleshooting

In a troubleshooting task, the student recorded various videos of the car under various conditions and then slowed down on computer to analyze the problems in staying within the line. The student then created an Arduino test to see how long the sensor readings and PID controller computation takes. It was observed that the mechanics of the car were causing the problem, due to an excessive actuation delay. In general, when encountering problems such as this, a four-step process was followed:

1: Based on observation, detect unexpected behavior of prototype.
2: Diagnosis, naming and clearly defining the problem.
3: Proposed explanations.
4: Proposed corrective actions.

H. Haphazard or Linear vs Managed and Iterative Designing

This was one of the dimensions where the student made the most significant progress. While initially expressing frustration when the car did not behave in a satisfactory or expected fashion, the student later recognized that these were the instances where the deepest understanding of the system was developed. The student made remarkable improvements relevant to this section. He realized that constant reformulations of problems and solutions are necessary to any good design process.

I. Tacit vs Reflective Design Thinking

The student kept a research journal where, every day, he would jot down the main points as to his progress on tasks, as well as reflectively analyze progress. The journal was kept up-to-date throughout the seven week progress and served as an excellent tool for thorough reflection once the summer experience was concluded.

The following diagram provides a visual representation of the progression the student made over the course of the seven weeks in each of the matrix dimensions.

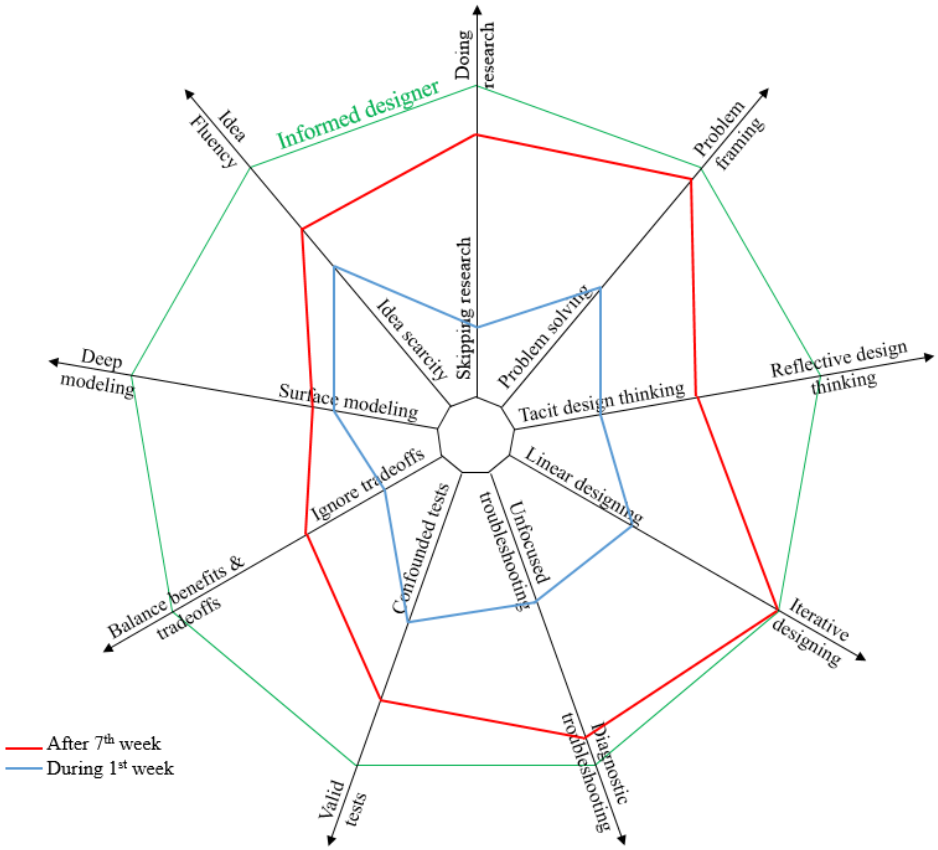


Figure 10. Student assessment before and after the research experience

In addition to the above assessment, in terms of general affective student satisfaction, the feedback from the student about the project was very positive. The student was very proud of the research and design work he accomplished, which set him apart from his classmates in his coursework.

Challenges and Opportunities Revisited

We will now revisit some of the challenges and opportunities mentioned at the outset and share some insights that may be valuable for other instructors who may wish to attempt undergraduate research experiences in similar settings.

Regarding the limited budget and resources, we hoped this would increase the student's careful planning and researching before moving forward with purchasing components. We feel this was indeed the case for this project. The student displayed the expected thoroughness in considering various possibilities before making permanent changes to the hardware. The limited resources associated with the project also effectively pushed the student to find more creative solutions to develop a working algorithm without resorting to simply buying more expensive equipment.

We framed working on a multidisciplinary project as an opportunity for student growth, increased communication skills, and increased abilities at fields outside his own concentration. In this regard, the project was extremely successful. Towards the end of the seven weeks, the student delivered a presentation to faculty and fellow students from various disciplines in the college. The reception of the student's work was very positive. The student also had to venture beyond his comfort zone to overcome numerous conceptual difficulties and technical challenges, involving hardware, software, and analytical considerations.

The multidisciplinary nature of the project was also a valuable opportunity for professional growth for the faculty member. Through the opportunity to observe his students making tangible connections between the content from the lecture classes and the mechanical, electrical, and computer engineering content associated with the project, the faculty member has developed a richer experience both for mentoring future projects and for incorporating multidisciplinary applications into lecture-based theoretical courses.

Finally, both the student and the faculty member agreed that giving the students to pursue research projects involving unfamiliar material successfully provided the student with very meaningful benefits. In particular, the students came away with an increased sense of how the theory learned in the classroom carries over to solving problems in practical applications, as well as how, in order to solve a problem effectively, it may be necessary to integrate knowledge and techniques associated with various disciplines. The student made very significant improvements in his path from "beginning designer" to "informed designer."

Based on all these insights, and in spite of the limitations already discussed, we would strongly recommend interested faculty members in liberal arts colleges (or other small schools with similar conditions) to explore the learning and mentorship benefits of crafting a similar one-on-one multidisciplinary undergraduate research experience.

Bibliography

1. M. Horauer, Dr. B. Chen, and P. Zingaretti, "Mechatronic and Embedded Systems Pave the Way for Autonomous Driving," http://sites.ieee.org/itss/2013/08/22/y13n1/, 2013, (accessed May 2014).
2. A.-M. Amancea, I. Doroftei, A. Barnea, F. Adăscăliţei, "Design and Implementation of a Mechatronic System for Lower Limb Medical Rehabilitation," *International Journal of Modern Manufacturing Technologies*, vol. 4, no. 2, Dec. 2012.
3. E. Graether, and F. Mueller, "Joggobot, A Flying Robot as Jogging Companion," in *Proceedings of the CHI '12 : CHI Conference on Human Factors in Computing Systems*, Austin, TX, May 2012.
4. Y. Li, G. C. Y. Chong, and K. H. Ang, "PID Control System Analysis and Design," *IEEE Transactions on Control System Technology*, vol. 13, no. 4, Jul. 2005.
5. D. P. Crismond, and R. S. Adams, "The Informed Design Teaching and Learning Matrix," *Journal of Engineering Education*, vol. 101, no. 4, Oct. 2012.
6. B. Layng, D. Cain, K. McNulty, R. O'Connor, and T. Estrada (faculty mentor), "Design of an Autonomous, Line Following Pace Car for Athletic Training," Zone 1 ASEE Confereence, University of Bridgeport, Bridgeport, Connecticut, April 2014.
7. J.E. Speich, S. Yingfeng, and K.K. Leang (2008, December). "Low-Cost IR Reflective Sensors for Submicrolevel Position Measurement and Control," in IEEE/ASME Transactions on Mechatronics, 13, pp. 700-709.
8. M. P. Hans, AAAI. (1988). "Association for the Advancement of Artificial Intelligence. Sensor Fusion in Certainty Grids for Mobile Robots," AI Magazine, Vol. 9, No. 2.
9. K. Moshe, X. Zhu, and P. Kalata (1997, January). "Sensor fusion for mobile robot navigation," in Proceedings of the IEEE, Vol. 85, No. 1, pp. 108-119.
10. G. Meijer, M. Pertijs, K. Makinwa, Smart Sensor Systems: Emerging Technologies and Applications, 2nd ed., John Wiley & Sons, New York, 2014.
11. R. L. Mason, R. F. Gunst, J. L. Hess, Statistical Design and Analysis of Experiments: With Applications to Engineering and Science, 2nd ed., John Wiley & Sons, New York, 2014.
12. J. Mandel, the Statistical Analysis of Experimental Data, Courier Corporation, 2012.
13. J. E. Clark, S. Kim, M. Cutkosky (September. 2001). "Design and Tuning for High-speed Autonomous Open-loop Running," The International Journal of Robotics Research, Vol. 25, No. 9, pp. 903-912.
14. A. G. O. Mutambara (1999). Design and Analysis of Control Systems, CRC Press, London, pp. 232-345.
15. R. C. Dorf, R. H. Bishop, Modern Control Systems, 12th ed., Pearson Education, Upper Saddle River, NJ, 2008.
16. MathWorks, "Introduction to Automatic PID Tuning," http://www.mathworks.com/help/slcontrol/ug/introduction-to-automatic-pid-tuning.html, 2014, (accessed May 2014).
17. K. J. Åström, T. Hägglund, C. Hang, W. K. Ho (August 1993). "Automatic tuning and adaptation for PID controllers," in Control Engineering Practice, A Journal of IFAC, the International Federation of Automatic Control, Vol. 1, No. 4, pp. 699–714.

Appendix

A. Evidence for the need of an algorithm of self-calibration

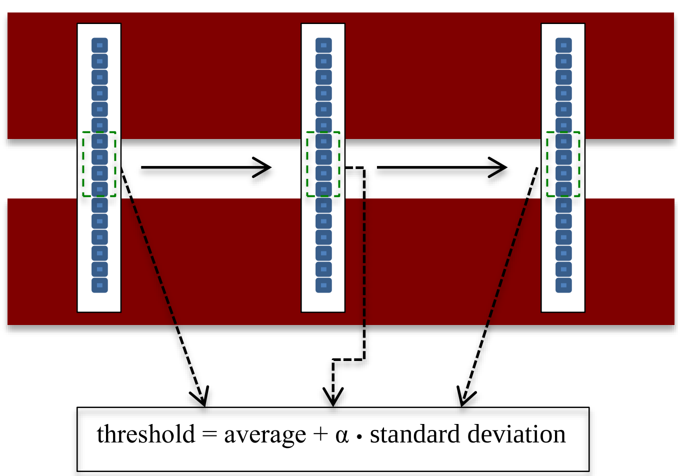
Table 2 below verifies assumed differences between several cases of operation, which is why the algorithm of self-calibration needed to implemented.

Table 2. Differences between black and blue values returned by IR sensors

15	14	13	12	11	10	9	8	7	6	5	4	2	1	0
26	24	25	24	24	**555**	**683**	**642**	**643**	**620**	26	25	25	26	27
26	24	27	24	26	**509**	**563**	**552**	**636**	**685**	33	27	27	26	26
26	25	26	25	25	**267**	**651**	**703**	**706**	**513**	27	26	27	26	25
25	24	25	24	24	**30**	**32**	**33**	**31**	**31**	26	25	25	25	27
26	25	25	24	26	**31**	**31**	**31**	**32**	**33**	28	26	25	25	26
24	24	25	24	25	**31**	**33**	**32**	**32**	**32**	27	26	26	27	26

B. Self-Calibration Sequence

The main challenge of the research project was to make the vehicle follow every kind of line. This could be done by performing a self-calibration sequence during the initialization of the car. The self-calibration is responsible for defining the threshold value for a given case of operation. During initialization, the pace car records 3 different sets of values for the line and computes the average and standard deviation for the recorded data (Figure 5).



(1)

Figure 5. Principle of the self-calibration

In equation (1), the coefficient, α, was statistically determined based on track quality, to set a threshold value, or average, about halfway between the high and low values. The track quality is another output of the sensor fusion, as seen in Figure 1. A certain number of LEDs light up and a message displays on the LCD screen of the pace car to inform the user about the difficulty in performing the steering control algorithm for a given case of operation, based on the self-calibration.

Coefficient α and Track Quality

Coefficient α aims to complete and relay the algorithm of self-calibration, if this one fails to return satisfactory results during the initialization of the car. A statistical analysis allowed the research team to assign a different coefficient α to each case of operation. The threshold set thanks to the coefficient α aims to fairly separate the line and the lane values. (Figure 6).

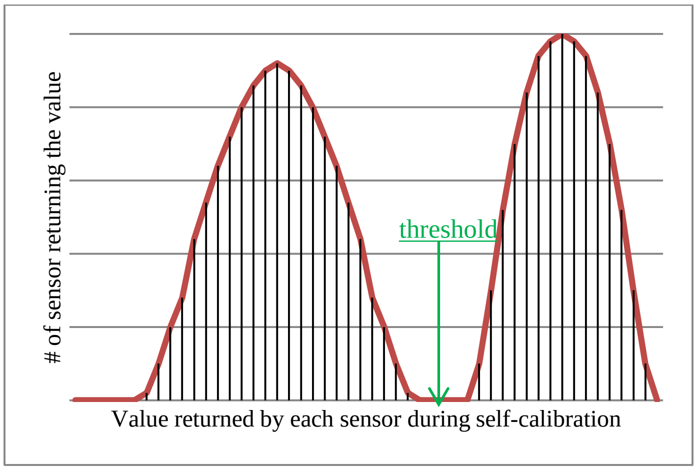


Figure 6. Coefficient α principle

One major obstacle to the successful execution of the algorithm of steering control is the imperfection of the surface on which the car is running. After conducting multiple tests, the research team noticed various impurities on the running surface, primarily on outdoor athletic tracks, due to wear and meteorological conditions. Hence, a statistical analysis is performed prior to self-calibration, to efficiently find an indicator of the track quality. This function simply tests the uniformity of the lane values and line values by computing both mean value and standard deviation, to return a numerical track quality indicator, which will inform the user whether or not the given case of operation if feasible. In order to numerically determine the track quality, Q, an equation that effectively ranks each situation was elaborated.

Additionally, serious wear marks were noticed on the Elizabethtown College outdoor athletic track, which makes it one of the most difficult cases to achieve (Table 3). On the other hand, readings were collected from the new outdoor athletic track at Alvernia University (Reading, PA), to quantitatively rank more than one typical quality of outdoor tracks. It was found that the analyses of these readings were much more conclusive, making it a far easier case. However, the majority of the feasible cases remain the colored lines inside the gym, where the surface is perfectly smooth and the edge of the line sharp.

The research team initially tested 6 distinct equations for the track quality indicator, Q, but only equation (2) could adequately rank the cases that were considered, where $\overline{Y}$ and σ_Y respectively represent the mean and the standard deviation for the line, while $\overline{X}$ and σ_X represent the mean and the standard deviation, respectively, for the surface around it.

$$Q = \frac{(\overline{Y} - \sigma_Y)^2}{(\overline{X} + \sigma_X)^2} \tag{2}$$

Furthermore, a certain number of LEDs light up and a message displays on the LCD screen of the pace car to inform the user about the difficulty in performing the steering control algorithm for a given case of operation.

Table 3. Track quality outputs

Case of Operation	Q	LEDs
Black Line - Gym Floor	500	16
Dark Blue Line - Gym Floor	7	↑
Light Blue Line - Gym Floor	5	
Alvernia Athletic Track	3	
Grey Line - Gym Floor	2	
Elizabethtown Athletic Track	1.3	
Not Doable	1.1	3

C. Speed Control

The speed control system is composed of 3 essential segments: the Arduino microcontroller, the servo motor, and the body of the car, which serve as the controller, the actuator, and the plant of the system, respectively[13]. The functionality of speed control for this application is outlined in the schematic diagram below.

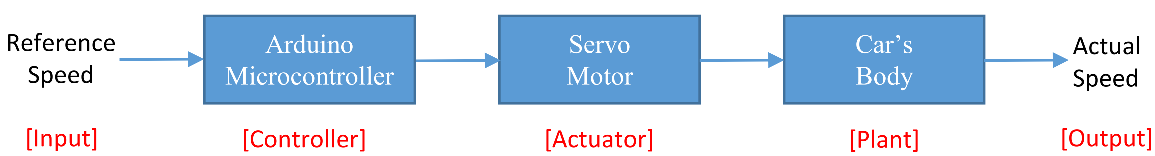


Figure 7. Open-Loop for Speed Control of the Pace Car

The user is able to specify the speed at which he wants to perform the training. The output of the given system is the actual speed of the car on the track, which might be slightly different than the requested speed, due to unprocessed external disturbances.

D. PID Controller

A PID controller was implemented by the research team in order to minimize the trajectory deviation of the car on the line on the athletic track. The PID controller was programmed in the Arduino microcontroller, which performed the relevant calculations to regulate the path of the vehicle. The code was logically divided into three sections; the proportional, integral, and derivative terms, which can be seen in the schematic diagram below[15].

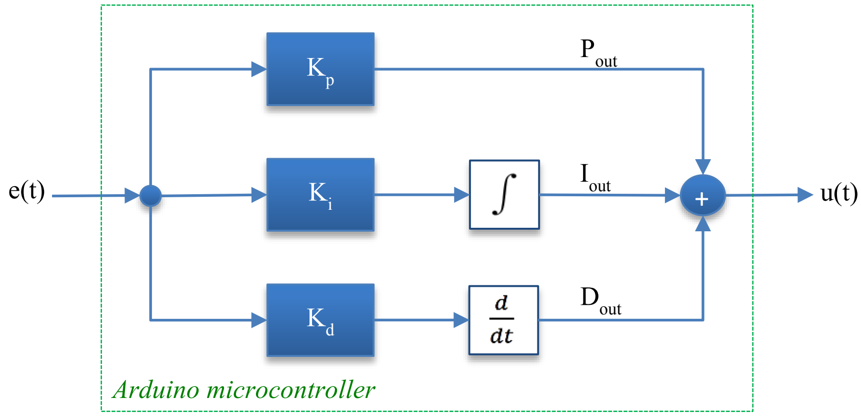


Figure 9. PID Controller Program in the Arduino Microcontroller

The coefficients K_p, K_i, and K_d serve as the proportional, integral, and derivative gains of the controller, respectively. The input e(t) is calculated during every cycle of sensor readings as mentioned in the previous section. The proportional branch of the controller simply multiply the input error by the K_p coefficient. The integral term is the sum of the previous errors and the instantaneous error that is being processed. The derivative term computes the rate of change in position over time using the instantaneous error and the previous one. These calculations are summarized in equations 3-6.

$$P_{out} = K_p \cdot e(t) \tag{3}$$

$$I_{out} = K_i \cdot \int_0^t e(\tau)d\tau \tag{4}$$

$$D_{out} = K_d \cdot \frac{d}{dt} e(t) \tag{5}$$

$$u(t) = P_{out} + I_{out} + D_{out} \tag{6}$$

Tuning Methodology

The tuning method consisted of experimentally adjusting the K_p, K_i, and K_d coefficients until the result was satisfied, since the mathematical model of the system was unknown. For this application, the result and output of the PID controller must be a corrected angle which will be assigned to the steering servo to allow the robot to smoothly follow the line. The proportional gain was first adjusted to achieve the desired transient response of the system. The integral gain was then selected to satisfy any steady state error requirements. The transient response was finally restored by selecting a suitable derivative gain[16,17].

Runs with different combinations of values for K_p, K_i, and K_d coefficients were performed on the outdoor athletic track at Elizabethtown College. Each run was objectively graded and ranked based on the ability of the car to follow the line. The optimal values for the coefficients were found by plotting a graph of the grade for each run.