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Introduction

This past summer, I had the incredible opportunity to participate in the CAT Vehicle Research Experience for Undergraduates (REU) at the University of Arizona in Tucson. The Cognitive Autonomous Test (CAT) Vehicle is used by the University's Electrical and Computer Engineering Department for research. Ten students from around the country studying computer science, computer engineering, or electrical engineering got to choose whether their project would be based on cognitive radio—how vehicles can communicate with other vehicles or with infrastructure, such as buildings and traffic signals, and verify the information—or autonomous systems—how the vehicle is able to control its motion and safely make real-time decisions.

After a week of learning some general information about cognitive radio and autonomous systems and some basic skills for using the software the CAT Vehicle uses, we were assigned research partners, a graduate student mentor, and a specific project to work on for the rest of the ten week program. My area of focus was autonomous systems, and my partner and I worked on developing a mathematical model to represent the internal dynamics of the vehicle. Our model could be implemented in a model predictive controller (MPC) to make predictions about future states of the vehicle. Based on these predictions, the controller could alter the vehicle's motion accordingly. This research experience allowed me to put my knowledge from a variety of courses into action, work with a diverse group of peers, and grow as an individual.

Overview of Research

During my summer research experience, I worked with a research partner and graduate student mentor to find a mathematical model to represent the internal dynamics of the CAT Vehicle. The CAT Vehicle is able to measure and record several parameters, such as velocity, steering angle, brakes, acceleration, and position according to GPS coordinates. The goal of our project was to take several or all of these parameters as inputs for our mathematical model to output predictions of the future states—velocity, steering angle, position, etc.—of the vehicle. A model predictive controller (MPC) would compare our model's predicted outputs to a predetermined reference trajectory or velocity profile. The controller would seek to minimize the error between the model's predictions and the given reference, and make adjustments to the vehicle's motion accordingly.

Our project mentor was working to get her doctorate in control theory. While our project goal was to create the mathematical model, our mentor would be able to implement our model on the appropriate MPC.

We based our project goals on work that had been done the previous summer to develop a mathematical model for the CAT Vehicle. The current MPC implemented a hybrid model, which switched between a kinematic and a dynamic model. The kinematic model could be computed very quickly and was typically used at faster speeds and small steering angles, when a coarser understanding of the vehicle's dynamics was sufficient for the model to make safe driving decisions. The dynamic model took longer to compute and as a result was used at slower speeds and larger turning angles, when a more detailed understanding of the vehicle's dynamics was necessary for safe operation. The hybrid MPC used a technique known as uncontrollable divergence to switch between the two models based on the driving conditions.

The goal for our project was to improve upon the current hybrid model predictive controller being used by the CAT Vehicle. We hoped to develop a model that was both more accurate and faster to compute than the current model. The challenge was to find a balance between accuracy and computation time. Though making a mathematical model more sophisticated often makes it more accurate, the added complexity increases the computational burden of the model on the system. To achieve our project goal, we would have to find a way to make our model more accurate than the current model without making it exceedingly complex in order to lessen the computation time.

We used a method known as system identification to develop our model. System identification involves conducting many experiments and collecting a lot of data which can be used to create a mathematical model. The experiments we designed had to test typical driving conditions, and we had to repeat each experiment several times to gather a representative sample of data under these conditions. My partner and I decided to break driving into two tasks: straight lines and turns. We designed experiments that involved driving in a straight line at different velocities and turning at various steering angles at different velocities.

In order to tackle the various aspects of our project, my partner and I learned about system identification, control theory, mathematical modelling, filter design, statistical analysis, and controller design. We conducted a literature review and read papers regarding model predictive control, hybrid model predictive control, hybrid mathematical models, model development, and predictive models for autonomous vehicles. We read through the CAT Vehicle's user manuals to understand the dynamics of the vehicle. We spent a significant amount of time investigating the GPS used by the vehicle and how to increase GPS accuracy through calibration methods and offline filters for the data. Having experienced the struggle of working with real data—which can be distorted by system or sensor noise—we designed unique filters for the data of each parameter measured in our experiments. We used system identification tools in MATLAB to develop a number of different mathematical models with various inputs and outputs, and verified these models using validation data sets from our experiments.

By the end of the program, we had developed a mathematical model for the controller that managed the velocity of the CAT Vehicle. This controller took velocity commands from the users and matched the vehicle's actual velocity to the commanded velocity. Because our model was developed using system identification techniques, it was based on a more representative sample of data from the vehicle and, as a result, was more accurate and efficient than the previous model for this controller.

The last day of the program was a demonstration day, where each research group was able to demonstrate the progress they had made in their research on the CAT Vehicle. For our demonstration, my partner and I decided on a velocity profile, which was given to a Proportional Integral Derivative (PID) controller we designed to implement our model. Our PID controller successfully managed the velocity of the vehicle autonomously by using the model we developed to follow the velocity profile.

Though we did not quite meet our project goals, we had improved one of the vehicle's controllers by developing an accurate and efficient mathematical model. It was incredibly satisfying to see our hard work implemented on the CAT Vehicle in real time. Our project was challenging, educational, and incredibly satisfying to work on. My partner and I learned a lot and had the opportunity not only to work with several graduate students, but also our own peers and collaborate on the complex issues in all of our projects.

Research in Connection with Courses

Though I learned about a number of areas of research that I was completely unfamiliar with at the beginning of the summer, my research experience also gave me the opportunity to put the knowledge and skills I have acquired from my courses at Monmouth College into practice.

I had participated in research experiences before this summer through opportunities presented to me at Monmouth College. During the summers before my freshman and sophomore years, I did research with Dr. Michael Sostarecz and several other students in the High Speed Imagery Lab as a member of the Summer Opportunities for Intellectual Activity (SO*f*IA) Program. We were able to explore applied mathematics through computationally and visually interesting videos. My freshman year, this experience introduced me to the research process. As a sophomore, I got the opportunity to serve as a student and project mentor to several freshman.

Throughout the course of my freshman year, I did independent research with Dr. Sostarecz in the High Speed Imagery Lab. I worked with the flow cell to investigate water flows around an air foil at varying degrees of attack using a technique known as particle image velocimetry. Every week, I would update my professor on my progress, take his recommendations into account, follow any direction he gave me for the week, and determine how to achieve my goal. At the end of the year, I put together a poster presentation and presented my research to faculty and staff members at Scholars Day.

My previous experiences in SO*f*IA and independent research influenced my work habits this summer. I understood the significance of working in a laboratory, handling lab equipment responsibly and safely, working under supervisors, independently solving problems, and presenting results to students and faculty. My research at the University of Arizona further emphasized the importance of safety when working with lab equipment, because in this case the equipment was an autonomous vehicle, which could cause damage to property or injury to people if mishandled. Over the summer, I was challenged to solve more complex problems independently, often with less direction. My graduate student mentor or the professors would point out problems with our experiment design or our research plan, and though they may have given us some ideas for fixing the problems, my research partner and I were often left with open-ended problems that could be solved a number of different ways with varying results. I also gained experience working with real data and writing the scripts or programs that would manage the raw data. This differed from my previous research experiences, in all of which the process of writing code to process data was closely guided by my supervising professor or by a fellow student who was familiar with the process.

By observing the connections between my previous research experiences and my experience working with the CAT Vehicle, it becomes apparent how my independent research and SO*f*IA research contributed to my work this past summer. Furthermore, by recognizing the differences between these experiences, I have learned how my research habits were improved with exposure to a different research environment.

My summer research experience also relates to courses I have taken for my mathematics and computer science majors. I was able to utilize my working knowledge of programs such as Octave and MATLAB, which I had acquired through my research and Numerical Analysis course, to process the data from the experiments run in the CAT Vehicle. In fact, because we collected such large amounts of data from each of our experiments, all of which had to be filtered and processed, I learned much more about MATLAB and have been able to apply this knowledge in my courses this semester.

In trying out different models for the CAT Vehicle and the velocity controller, I was able to see how knowledge of differential equations could be used in models. The model that was used in the CAT Vehicle at the beginning of the summer relied heavily on differential equations, and my understanding of this topic based on my Differential Equations and Calculus III courses not only allowed me to understand how the controller in the vehicle worked, but also gave me an idea for how to start fitting models based on our experiments.

My introductory computer science and programming courses have taught me valuable programming techniques and good practices to follow when writing code. One such practice is making comments throughout a program for clarity and for future reference. While I was writing code for processing data, I was able to put these techniques into practice so that my research partner and graduate student mentors could understand my code. Comments throughout my programs also made it easier for me to recall what I had done weeks before, which was valuable near the end of the program while we were wrapping up our project.

This semester, I am taking a course on Artificial Intelligence, which has allowed me to apply and reinforce some of the knowledge I acquired over the summer. I have been able to learn more in depth about many of the concepts that formed the foundation of my research in autonomous systems. For example, I have learned more specifically about the agent-environment framework, which on a high-level is similar to how the CAT Vehicle received information from its environment and chose appropriate actions to take. I have also utilized my newly acquired familiarity with programs such as MATLAB to work with large sets of data for projects involving machine learning.

I found that my Honors courses also influenced my summer research experiences. The Honors Program has taught me to be open minded, especially when confronted with unfamiliar ideas. I have learned to embrace having my perspectives challenged and to challenge others' perspectives. This summer research experience exposed me to diverse individuals from all over the world, whose lives, experiences, education, and work ethics are different than mine. I was challenged to consider a graduate school education—which I had previously not considered as an option for myself—and by the end of the summer was convinced of its merit. I was exposed to new ideas, people, areas of research, and potential futures for myself that I had never considered before. Because of my experience being challenged in the Honors Program, I was able to meet these challenges confidently, learn from any difficulties, and grow as a result.

Many of my past research experiences, major courses, and Honors courses have in some way provided me with knowledge or skills that were beneficial to my research at the University of Arizona. In addition, I have already been pleasantly surprised at how everything I learned this summer can be applied to some of my higher level major courses. I am sure that the research skills and focused work ethic I used working with the CAT Vehicle will also be implemented during research for my capstone projects here at Monmouth College.

Reflections on Personal Growth

Not only did my summer research experience allow me to grow in academic and intellectual contexts, but it also provided numerous opportunities for personal growth. The personal growth ranges from my relationships with peers, my own strengths, and my plans for my future education and career.

Though the SO*f*IA Program has given me the opportunity to work with small groups of individuals on a project, I had never before worked with such a large and diverse group on a research project before. The students selected for the program were from around the country, meaning we all had different experiences and interests. Despite our differences, we were able to work together, share ideas to better each other's projects, and even form lasting friendships. The diversity of experience and thought in the program allowed me to practice working with others, listening, sharing my perspective, and finding common ground to connect.

Not only have I grown in my ability to manage group dynamics, but I have also grown personally as well. My communication skills have improved, specifically when it comes to precision and succinctness of language. In communicating with my research partner, graduate student mentor, the professors who ran the program, and graduate students or peers involved in projects other than my own, I found that particularly in a research context, it is important to express ideas clearly and without superfluous words that could confuse meaning. Even on an interpersonal level, my communication skills improved because I had to express my ideas and my experiences to people who knew nothing about me. Through meaningful interpersonal communication, I was able to make friends that I still maintain contact with.

I have also become more confident as a student studying mathematics and computer science. Prior to attending this program, there were many times I would tell myself I was not capable of doing something or succeeding in a certain field. However, having worked on an advanced research project which involved overcoming all sorts of challenges, I know that my current abilities do not necessarily dictate my future success because I can always take advantage of the opportunity to learn, experience, and grow. Over the summer, I read and learned from research papers put together by graduate students or even experts in their fields, and utilized this information throughout the many phases of my project. I use minimal previous knowledge and taught myself how to use MATLAB, which I used regularly to process the data from our experiments. I have a working—if basic—knowledge of concepts studied in graduate school, such as control theory, autonomous systems, and artificial intelligence. I met complex challenges with severe implications for our project and the potential safety of our experiments, and overcame these challenges by researching, asking questions, using the resources available to me, trying new things, sometimes failing, learning from my mistakes, and persevering. Because of these experiences, I have improved my research and problem solving skills. I feel more confident in my ability to solve problems and achieve in situations where I have little to no previous experience. This confidence has allowed me to persevere even when part of me believes I will fail, hold myself to a higher standard of excellence, and set more ambitious goals for myself.

Some of the new goals I have set for myself are directly inspired by my experiences in the CAT Vehicle REU. I am sure that I want to go to graduate school, and my ambition is to attend one of the best graduate school programs in the field I choose. I am considering programs in pure mathematics, autonomous systems, robotics, or, ideally, artificial intelligence. Prior to my experience this summer, I would never have thought I could succeed in graduate school, especially in the fields of robotics or artificial intelligence, despite those being ambitions of mine. But now, I have confidence in my ability to learn, teach myself, work hard, and achieve. Throughout the summer, I would find myself forgetting to eat, sleep, or take breaks because I was so passionate about the research I was doing. I now know that if I find something that I love and can lose myself in, I will put in the effort and hard work to achieve my goals.

I also hope to find a career that involves doing research. The process of educating myself on the current successes of a field, finding what questions still need to be answered, experimenting, processing data, implementing ideas, learning from mistakes, and trying to meet the goals I set for myself was incredibly engaging. I found myself eager to get to work every day. As a short term goal, I hope to put my newfound love of the research process to good use when I begin my capstone projects for my mathematics and computer science majors and for the Honors program within the next year.

Conclusion

My experiences in the CAT Vehicle REU taught me so much about autonomous systems and autonomous vehicles, graduate school opportunities, professional and interpersonal communication, applying my knowledge from courses I have taken, learning new things, the research process, myself, and my ambitions for the future. I was faced with many personal challenges and challenges in the context of my project, all of which I eventually overcame through hard work, open-mindedness, passion, and perseverance. In this past semester alone, I have applied so many of the skills and practices I learned over the summer, and have experienced the mutual support of new friendships. This research experience has not only changed my perspective on research and my ambitions for the future, but also how I carry and view myself and my abilities. My time at the University of Arizona working with the incredibly intelligent professors, graduate students, and my fellow students at the CAT Vehicle REU will influence the rest of my undergraduate experience, my graduate school pursuits, my future career, and the direction of my life.