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January 4th, 2002

Dr. Andrew Rawicz
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RE: *ENSC 340 Project HockeyJACK - Automated Air Hockey Player*

Dear Dr. Rawicz,

The attached document, *Hockey JACK Process Report*, outlines the process through which our team designed and implemented our automated air hockey player system. The goal of our project was to design and build an air hockey player that could detect puck movement and intelligently block the human player's attempt to score.

This report documents the current state of the device, deviations from original plans and the future plans for the device. Finally, we outline some of the limitations in budget and time we encountered and detail the technical and personal experiences gained by each team member.

JACK'D Games consists of five dedicated fourth year students: David Boen, Judy Cha, Alex Kwan, Clarence Wong and Kevin Yoon. Should you have questions or require additional information, please contact us via email at 340-jack@sfu.ca.

Sincerely,

Judy Cha, VP External
JACK'D Games

Enclosure: *ENSC 340 Hockey JACK Process Report*

Process Report for the

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Hockey JACK

Automated Air-Hockey Player Design Group

Submitted by:	JACK'D Inc. Dave Boen, Judy Cha, Alex Kwan, Kevin Yoon, Clarence Wong
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Date:	January 4th, 2002

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Glossary

Term	Definition
Mallet	The striker piece that is used by the player to strike the puck.
Rink	The arena surface in which the game is played.
Goal	The horizontal slots on either side of the rink.
Centerline	The line the runs along the center of the rink. Parallel to short-side of rink.
CPLD	Complex Programmable Logic Device. A fast, configurable logic device containing flip-flops and combinatorial logic.
PWM	Pulse Width Modulation. A technique enabling control of servo motors, by varying the duty cycle and pulse width of a signal.
Rack	The device laid across the short side of the rink to guide the HockeyJACK's mallet.
Arm	The device that extends from a servo motor located behind the rink to the rack in order to control the lateral position of the mallet.
RAMA	or Rack-Arm-Motor Apparatus™, consists of the 3 components that make up the mallet controller mechanism.

1 Introduction

Over the course of the semester, developing the ultimate automated air-hockey player has absorbed the talents of five hardworking and tireless individuals – David Boen, Judy Cha, Alex Kwan, Clarence Wong and Kevin Yoon. This report analyzes the process through which the idea progressed from nascent dream to final reality and documents the lessons learned by each individual member.

2 Current State of the Device

As described in the functional specifications, the HockeyJACK system intelligently operates a hockey mallet blocker in response to inputs from a grid of IR sensors. Figure 1 illustrates the process by which the HockeyJACK system operates.

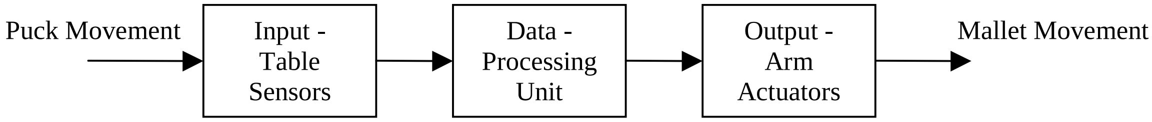

Figure 1: System Block Overview

The IR table sensors detect differences in the distance to the hockey table. When a puck passes underneath the sensor, the signal level changes. The change is converted to digital form and sent to the data processing unit.

The data processing unit reads the digitized sensor inputs computes the trajectory of the puck. Based on the computed trajectory, a reasonable guess can be made as to the future movements of the puck and the arm can be activated to block. The data processing unit consists of two distinct parts. A low-level interface board contains sensor buffering, PWM servo signal generating, and computer parallel port capabilities. A standard Pentium PC computer handles the higher-level decision-making process (a custom algorithm) and interfaces to the interface board through the bi-directional parallel port. A wooden mount was built to secure the system. On top of the mount, the sensors, the arm, and the rink lie in a relatively fixed position. Arm movement is provided by a servo motor, which is powered by a separate heavy-duty power supply.

From our tests, the system responds well to reasonably fast puck movements. The arm can react to approximately 90% of all straight-line shots and has an approximately 70% chance of blocking banked shots off the side of the hockey rink.

3 Deviation of the Device

3.1 Overall System

At the end of the project term, we achieved what was planned. The prototype system detects puck movement and actuates the blocking mallet in response. There were minor problems, such as the handling of bank shots and the robotic arm safety precautions, but they did not affect the overall system performance significantly.

The prototype consists of three distinct electronic subsystems. The arm control and computer interfaces boards are located on separate circuit boards, mounted on a clear, acrylic base. The sensing system is located on nine separate circuit boards attached to the RAMA structure. The computer interface and sensing system utilize a common, wall mounted power supply, while the arm uses a computer power supply.

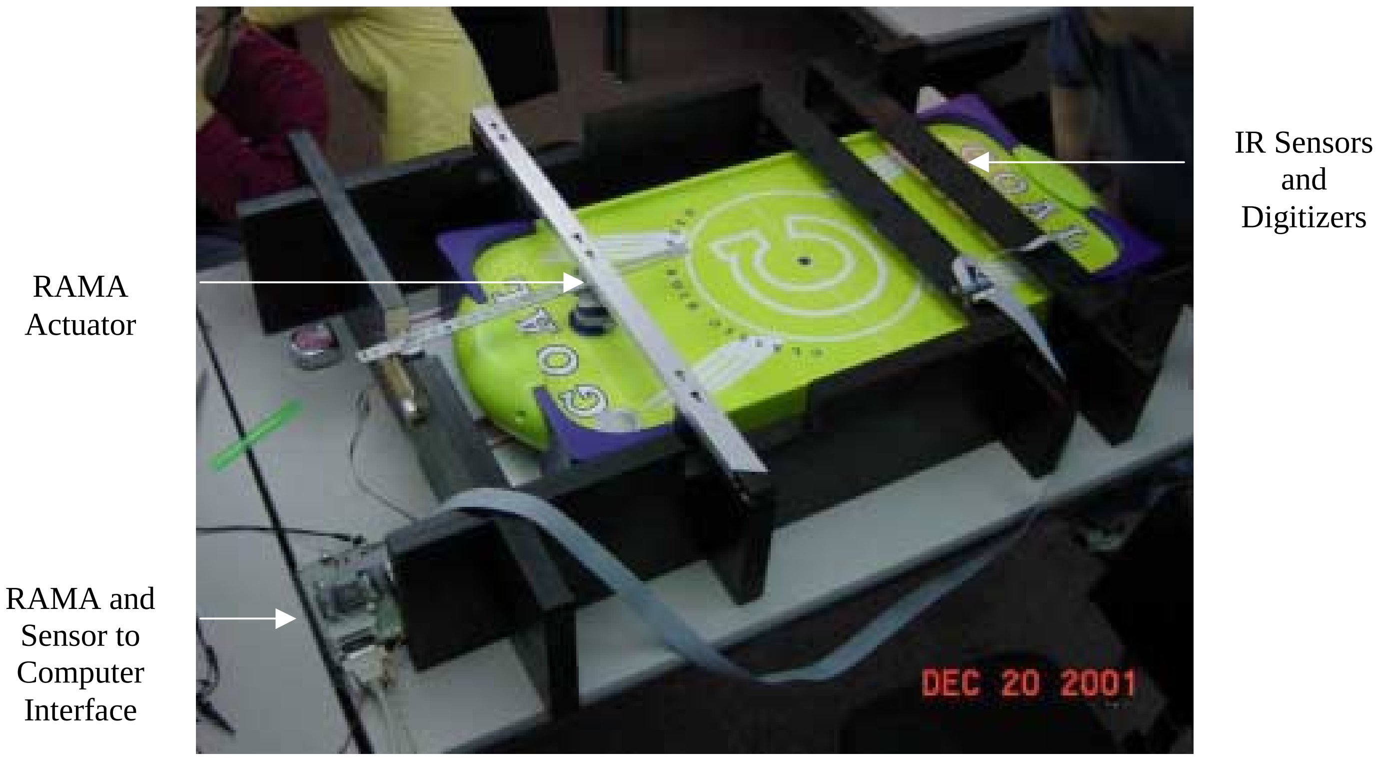

Figure 2: The HockeyJACK System

The system is adaptable to any table of similar size and can be disassembled and reassembled with minimum effort. Furthermore, the circuit boards are exposed and no attempt was made to package or refine the appearance of the system.

3.2 Sensor System

The sensor system has been constructed as specified in the original design specification document with a few minor electrical circuit design modifications. The physical layout of the sensor system however has been carried out exactly according to the design specifications.

The system currently has two rows each consisting of twenty sensors, which are aligned 2 cm apart from each other as originally planned. The sensors are placed approximately 5 mm above the air hockey table for the puck detection. The distance between the two rows and the distance between the one end of the table and the first row are adjustable, as specified in the design specification document.

The first noticeable deviation is realized in the way the multiplexor multiplexes the sensor outputs. The original idea was to multiplex five every fifth sensor outputs for the optimum detection of the puck. However, to achieve this, very complicated wiring was required. Hence five adjacent sensor outputs were multiplexed which were easily achieved. This does not affect the puck detection since the sampling clock is fast enough.

A 1 V voltage supply was also buffered which was not considered in the original design. A small voltage drop in the voltage supply was observed during the testing of the sensor system. Even though the voltage drop was very small, the sensor performances deviated significantly because the intensity of the IR light is an exponential curve to the 1 V voltage supply. The voltage buffer eliminated the voltage drop, resulting in very reliable sensor performances.

Additionally, LED's were added for each sensor for the testing purposes. The LED activate when the sensor detects the puck. This extra feature helped us greatly in debugging.

3.3 Processing Unit

Implementation of the Processing Unit hardware and software did not significantly deviate from the requirements set forth in the Design Specification. However, minor deviations occurred, due to time and hardware constraints.

Currently, the Processing Unit consists of two distinct parts: a low-level interface board containing a Complex Programmable Logic Device (CPLD) with code to operate a PWM signal for a servo motor and IR sensor buffering, and a Pentium computer to handle higher level algorithm and sensor data processing.

Firstly, the Processing Unit does not utilize the Enhanced Parallel Port (EPP) protocol set forth in the design spec to transfer sensor data between the interface board and computer. This feature was not available due to the limited budget and age of the computer purchased for the project. However, this did not prove a major concern, as software was developed to emulate the protocol.

Secondly, the data transfer between interface board and computer does not proceed as smoothly as intended. Originally, a single command of all zeros sent from the computer was meant to start a new sensor update. However, the computer could not easily inform the interface board which sensor data byte to send. Therefore, separate addresses are sent from the computer to the board for each byte requested, doubling the time taken to retrieve and update the sensors.

Lastly, the pushbuttons implemented on the interface board are unutilized due to space limitations on the CPLD device. Originally intended for manual control of the arm, the functions required to debounce the button inputs proved too large for the CPLD to handle.

3.4 Arm Actuator

For the most part, the arm actuator has been constructed as outlined in the design specification document. An RC servo receives the position-defining pulse-width-modulated signal from the processing unit after it has calculated the trajectory of the puck based on the sensor information. A 16 ms clock with a duty cycle varying between about 1 and 2 ms define the degrees of motion required to cover the entire width of the air hockey rink. At the software level, a resolution of approximately 1.8 degrees was implemented. This translates to a maximum step distance of about 1 cm providing sufficient precision of puck placement, given a puck diameter of 5 cm.

Some issues were encountered with the manner in which power was provided to the servo. We decided that the servo motor deserves its own separate power supply, since the motor could draw a large current during its operating phase. And since such a motion phase took a very short time, the resultant current spike might cause ground distortion to other parts, most notably the digital electronic components.

Initially, a simple 6V, 1A AC/DC power supply was used, but the voltage levels were found to drop when current increases. This was unacceptable for servo operation, since the motor required constant voltage, at high current. We found that if the current dropped too significantly, then the servo motor will jitter around its final position. The solution was the power supply from an old computer. The fanned power supply provided a constant 5V outlet and could support as much as 120W of power. This was more than we needed for reliable servo operation.

One alteration from the design specification is the design of the arm. Instead of using the keyboard sliding unit, the arm was custom-designed with a piece of aluminum. The new design is the exact replica of the conceptual arm in the top view diagram in the Project Proposal. The length of the aluminum piece acts as the arm. And to provide the sliding contact, the central part of the piece is drilled. This new arm design proved to be lighter and less expensive than the initial design.

3.5 Algorithm

The computer algorithm is developed on the QNX real-time operating platform. It is used to determine the puck trajectory from the sensor data, and then compute and command arm movement.

Initially, the algorithm was designed using high-level block diagrams. During actual implementations, these ideas were translated into code using the C programming language.

In the translation, there were many problems. One problem was the need for a shared memory structure. Since the system must run in real-time, the algorithm must be written in multiple parallel processes. These processes can only exchange data when a shared memory structure is set up. Since the initialization of shared memory in QNX differed between versions, much effort was put to re-learn the newest version of the operating system.

Another problem is the determination of bank shots. Bank shots are trajectories that touch the wall at least once. Initially, the trajectory of bank shots was simple in design. The laws of physics were applied, and since the angle of reflection equals the angle of incidence for an elastic collision, mathematics simplifies. But in real life situation, the wall of the rink absorbs much of the incoming force of the puck, and therefore the reflected path can deviate from the actual path by as much as 30 degrees. There is no immediate remedy for this problem. At the moment, an adjustment factor was added in the calculation so the arm would be right most of the time. In the future, if wooden tables are used instead of plastic rinks, then the problem may be of less importance.

Finally, timers are added in the program to reset the arm after each block. This feature was added to ensure sufficient time for the arm to block the puck. The principle is simple: if the arm is in the center of the rink, then it will take less time to reach the left side compared to the arm that begins on the right side. Therefore, by returning the arm to the center position after each block, the action can be completed in a faster time. In more precise terms, the maximum required time is halved when the arm resets itself.

4 Future Plans

4.1 Overall System

- Package the System

At present, all the circuit boards of the various sub-systems are exposed, which may pose a safety hazard. One solution is to enclose the circuit boards within a plastic housing.

- Integrate the System Power Supplies

Currently, the sensing and computer interfaces use a wall power supply, while the arm itself is powered off a computer power supply. We hope to eventually power the entire system off a single, stable power source, activated by a single power switch.

- Develop the System in Multiple Rink Sizes

The system was developed for a 4 feet table. With additional scaling to the Rack and sensing systems, larger sizes of tables could be supported.

4.2 Sensor System

For the better and more reliable sensor system, several changes can be implemented in the sensor system in the future.

Currently, the sensor emits the IR light from the 1 V voltage supply. An increase in the voltage supply will result in more robust and powerful sensor performances. To achieve this, a more powerful supply is required and care must be taken to prevent the sensors from possible damages due to a high voltage supply.

Buffering the sensor outputs and comparator outputs can be considered for a more reliable system. The buffering of the outputs will rid the loading effects of LED's ensuring a clean digital high (5 V) as an input to the multiplexor. An amplifying stage should be added between the sensor outputs and the comparator inputs. In doing so, large load resistance could be replaced by smaller load resistance and still yield the same sensor sensitivity.

The calibration process can be automated by reading the reference setting on one of the sensors and have software to automatically adjust the reference voltages of the sensors under ambient conditions. This allows the sensor system to work under various environments without manual calibration. Additional circuitry would be required to achieve this purpose.

Accuracy of puck's detection could be improved by using some sort of linear optical sensors that covers the entire width of the table. The center of the puck can then be calculated from the mean of the distribution produced by the device. However, such device may need to be developed or the cost may be over-budgeted.

Finally, a PCB board should replace the prototype boards in the future. The limited time and budget for the project did not allow us to design and build the PCB board for the sensors. The PCB board will be more reliable than the current prototype boards.

4.3 Processing Unit

In the future, a number of improvements may be made to improve the processing unit's speed. Improved CPLD implementation, data transfers and board design are among the planed changes.

Firstly, the use of a computer with EPP hardware would eliminate the need to emulate the protocol in hardware and reduce the overhead in transferring data from the interface board to the computer.

Secondly, eliminating memory address transfers would certainly improve the data transfer rate. The EPP hardware has the ability to transfer 32-bit words rather than single bytes, which would eliminate the extra address transfers and increase sensor update speed. Using 32-bit instructions utilizes one 32-bit read and one 8-bit read to transfer the five bytes of sensor data from the interface board.

Thirdly, purchasing a larger, pin-compatible CPLD in the Altera MAX 7000 family would allow additional features to be incorporated, including the omitted manual arm control buttons. Additional sensor buffering would be possible, which might reduce the sensor error rates observed during the development of the system.

Finally, a more radical speed improvement might involve combining the features of the computer and interface board onto a single PCB board. A microcontroller would be used, with the elimination of the CPLD interface. Microcontrollers with onboard PWM interfaces would be ideal for such an embeddable device. However, multi-tasking and use of complex math functions would require additional hardware interfacing and software debugging to implement.

4.4 Arm Actuator

One feature that can be implemented in the future is the return strike. That is, the computer has the ability to strike the puck as a human player can, instead of simply blocking the incoming puck. To add this feature, the mallet holder will have to be redesigned. The design can possibly include a spring triggered by a solenoid, which is powered by the servo power supply. Of course, the addition of functionality to the mallet holder will unavoidably increase the mass of that the arm has to move and contribute to the overshoot tendency of the arm currently seen during larger swinging motions.

Feedback could smoothen out the operation of the servo motor. The overshoot is corrected internally by the servo, which causes an oscillatory motion that lasts for about half a second. In the future, a feedback system can be tuned to provide the best performance. A PID feedback controller can be added in the servo feedback loop to improve transient response.

4.5 Algorithm

While the algorithm is sufficient to block the puck in most cases, it can be improved upon. One improvement is to use a more accurate mathematical model. At the moment, the puck is treated as a point particle, which is inaccurate since it does not account for puck spinning and location of collision. Using the new model will also benefit bank shot determination. Additional calculations may be required for finding the impact of hitting the rink wall.

Another improvement is the incorporation of the concept of time into the algorithm. If the algorithm is aware of time, then the sensors input can be used more effectively to determine the position of the puck, since it would know the position with respect to time. And the next logical step would be to determine the velocity, and therefore calculate the time when the puck will hit the mallet. This is the logical next step if the arm is expected to hit and return the puck.

5 Budgetary and Time Constraints

5.1 Budget

The following table shows the proposed and actual budget,

Items	Projected Cost	Actual Cost
Air Hockey Table	$150	$180
Structural Materials	$200	$70
Actuators	$100	Borrowed
Sensors	$300	Samples from manufacturers
Microprocessors and Prototype Board	$200	$95
Electronic Components, Cables and Wires	$100	$105
Power Supplies	$50	Group member contribution
Miscellaneous	$50	$50
Sub-Total	$1150	$500
Contingency Funds (20%)	$230	-
TOTAL	$1380	$500

Table 1: Projected and Actual Budget

The actual budget is almost three times less than the projected budget. There were many factors that contribute to this reduction. First, many of the components were borrowed. For example, the SFU Engineering Faculty provided the CPLD device. Also, the use of readily available sources, such as a AC/DC cellular phone chargers and an old computer power supply cut the power supplies costs. Free samples from online manufacturers were used abundantly for the electronic parts of the project. All of the sensors, and most of the op-amp and comparators were free samples. Finally, crafting in the machine shop reduces structural materials costs.

Secondly, the reduction in budget was associated with table size. If a regular tournament air hockey table is used instead, some of the costs, such as sensors and electronics components, would be increased proportionally to the new dimensions.

5.2 Time

A Grantt chart is attached to this document (Appendix A) where the top portion represents the original expected completion dates and the bottom portion represents the actual task completion dates.

Most of the documents were delivered on time except the design specification that was delayed by a week. The delay was due to high concentration of other course work and the class was granted one week of extension. Officially, all deliverables were submitted in time.

In the early stage, we took much more time in researching for best solution of our application. This is due to an underestimation of the numerous electronics and mechanical parts we can choose from. However, the addition time spent on research results in good parts selection that helps to speed the design and implementation process.

One important thing to note was that the system designs were delayed almost a month from the expected start date. This was due to the late shipment of the air hockey table and we cannot finalize design until we get the exact dimension of the table. Other than this reason the duration of the design stage was successfully restricted to our expectation.

After all designs were done, implementations were postponed due to midterms. Implementations were again paused to before the final exams and were continued right after the final exams. The actuator and interfacing unit were completed in the expected amount of time while the sensor system took more time than expected due to the massive number of sensors to be mounted on prototype boards.

Testing and debugging were carried out throughout the design and implementation process. In particular, testing and debugging after all sub-systems were interfaced took about 1 week, which was reasonably well controlled.

In the end, we were able to deliver our demonstration one day before the planned date.

6 Inter-Personal and Technical Experiences

6.1 David Boen

From the technical perspective, I learned how to actually implement a CPLD board design and program it to satisfy a function. While I learned how to program such devices during coop work terms and in class, I had never designed a system from the hardware on up. In addition, the project enhanced my practical skills such as soldering and wire layout.

Personally, I learned how to group organizational and collaborative writing techniques. I also learned how to motivate group members and schedule group meetings. However, these four hard-working individuals needed little in the way of extra prodding to complete their tasks.

Effective communications skills are vital for a group project, especially a semester-long technical project. The design document is as important for the Group as it is for the technical coordinators. My advice is to have each group member read, understand and search for inconsistencies in the design spec. Reading each all the separate parts allows one to gain an understanding of how one's part fits in with the overall system. It was amazing to see the disparate parts of the system come together in the final week before the demo date without too much difficulty.

However, I found that incorporating the different parts of a project together took longer than anticipated. My group expected to have the system integrated well before the actual date and within a matter of hours. The actual integration took many days (and nights) of hard work, cursing and Coke to sort out. Remember to set aside enough time for integration, even for individual components that are supposedly "complete". In the end however, the project became more than the sum of it's parts.

Finally, I have come to realize that ENSC 340 does take up a significant portion of time. I do not recommend taking the full course load for maximum enjoyment of this class. I found myself working late Friday nights and weekends from the second month onwards. Still, I found this class extremely enjoyable and would love to take it again with an entirely new project.

6.2 Judy Jeeyoung Cha

Throughout this project, I have applied what I learned in the engineering analog/digital circuit courses to build the sensor system.

One personal problem I had was that I have difficulties in applying circuit theories to reality simply because I have doubts that the theoretical expectations would actually come true. Witnessing that the various analog circuits that the sensor system consists of actually work as they should was hence just like a magic to me. Coming up with circuit design solutions to achieve what I want and seeing them actually implemented in reality to work like a magic helped me solve my problem and gain some confidence in myself and things that I build.

Also, integrating all the sub-parts together to complete one whole system was an extremely valuable experience. Through the integration of the system, I learned to appreciate many different aspects of engineering fields that I before did not like and did not value much. Now I strongly believe that all the different engineering fields are equally important and essential for a successful system.

In terms of interpersonal skills, I had some good chances to get to know my team members more and appreciate their expertise and know-how's. I feel very luck to find such good team members who are hard working and easy to get along with. Finding an effective way to communicate with each other, cooperate, and compromise was essential for the team harmony. After completing our project, I believe that many great things can be achieved by a small group of dedicated and hard working people. And the proof is us.

6.3 Alex Kwan

I believe the project course is perfect for an engineer entering into their fourth year. Throughout the project, I learned how various parts come together to form the system. Parts, such as real-time system programming, analog circuitry, and digital field programmable controllers, are learned in separate courses. But through this project, I saw clearly their interacting role in a complete system.

More specifically, I gained valuable mechanical design knowledge from the project. Operating equipment, such as bandsaw, drill press, and the milling machine, becomes a daily routine during the final week. Also, since our system is not based on any prior designs, we were able to experiment with different new ideas that stretches our mind. One particular rule I picked up was to never make a change without checking the change three times. Once a change is made, it is usually very difficult to return it to the original form. That is the carefulness and predictive mind that all mechanical designers should have.

In terms of interpersonal experience, this project course lets me understand the potential of five hard-working engineers. Nothing is impossible, but completely these "impossible tasks" just may take a lot of time. Moreover, common working habits are required for a harmonized group dynamics. We are fortunate to have five group members who share the same enthusiasm for the project. When everyone is willing, the whole project becomes a blissful experience.

6.4 Clarence Wong

My main job responsibilities are building the sensor sub-systems and conditioning the sensor signals for interfacing to the processing unit.

During the sensor selection process, a lot of research was done on what types of sensors were out there in the market. I started with the high level application and functionality of the whole sensor sub-system and work back into lower level circuit implementation and parts selection. In this process, I learnt how to select parts those are suitable for our application. For example, to get the fastest response from a moving puck we decided that optical sensors would best fit our purpose.

In addition, figuring out how to layout the sensors to maximize the accuracy of puck detection is another challenge that requires a lot of "what-if" thinking. I learnt that a thorough motion planning for such mechanical system is a crucial factor to success.

Once the general layout and sensor type were determined, the research on various makes of optical sensors was another valuable experience. During this parts selection process, I was challenged to find sensors that match required system specifications while keeping the cost as low as possible. Also, I learnt a lot of about package selection, as I wanted to minimize the circuitry layout size for the sensor systems. An additional lesson I learnt is that always ask for sample parts when prototyping; only actual testing on parts will give designers a solid idea of how it is functioning.

Gaining experience in circuit design is another adventure for me. I found that circuit design is an iterative process where designer needs to experiment with actual behaviour of the parts and modifying the circuitry to condition the electrical signals. Another aspect I learnt is that breadboard testing is very different from soldering components onto prototype boards. Wiring on prototype boards could become very complicated without thorough planning, as it is one of the mistakes I made. If I spent more time on working out all the wiring, it would make the soldering easier and layout cleaner.

During the testing phase of the project, I encountered a serious problem with the sensors that they don't seem to work as specified in the data sheet. I was reluctant to go back to the data sheet at the beginning, and try to add more circuitry to resolve the problem. After a few circuitry modification attempts, the sensors are still not working reliably and I became stuck at that point. Good thing was Kevin came over and helped me sort things out a little bit. Although he didn't know much about the sensor system, he provided great insight of what was actually happening. With his inquiries about the sensor system, I learnt more about the design and found out the sensors were operating at a minimum condition. Two lessons were learnt - always read data sheet carefully, and explaining the design to someone unknowledgeable of it would develop greater understanding of the design.

In many aspects, interacting with different people would help the process go smoother. As an example, everyone took part of the motion planning and we consulted other professionals on this, the end result is a very complete and successful sensor layout decision. During the sensor design process, Judy and I were not reluctant to share ideas on what the circuitry needs, and we came up with a very nice and compact design in short time. Another example that is mentioned before is talking to people who are unknowledgeable of your system would help the debug process to go smoother, as every little details are explained to this person.

Interpersonal communication throughout the project is very important. Various tasks of the project can only be run simultaneously when different departments keep updating their status to others. I think our group communication went very well and this results in reducing the integration time significantly. Dave was very keen and kept asking about how the sensor system would be interfaced to the processing unit. His expertise and dedication has made the integration a very smooth one.

Overall, I felt the team executed very well and efficient as each member maximized his or her expertise to make this complex project especially enjoyable.

6.5 Kevin Yoon

Over the past four months, I have had the pleasure of working on a project that was said by some to be "quite an endeavor". As we looked closer into the complexity involved in making an air-hockey-playing robot, we all began to share some of the doubt that seemed to surround the completion of the project. Our success has, therefore, been that much more rewarding and proved to be a sweet justification of the countless hours spent and skills learned.

One of the technical things I've gained from this project is a further insight into the requirements of operating an RC servo motor which was used to drive the arm. This includes experimentation with the nature of the required control signal as well as various methods of supplying power.

Having helped to design the bulk of the RAMA, a large portion of my contribution to the project also lay in the design and construction of the mechanical framework of the game apparatus. Much of my time, therefore, was spent in the machine shop manufacturing various components (which sometimes included destroying various components and then gluing them back together). Given the precise nature of the project, precision construction of the mechanical parts was crucial; and I believe the experience has left me with a higher degree of competency in the shop environment.

Interaction with my fellow group members was, however, by no means lacking. Proper communication with the other departments was critical to smooth progression on all sides. I am glad to have had the opportunity to work with a group of such highly dedicated members. There were absolutely no problems in terms of group dynamics so it was always easy to focus on the project.

In retrospect, I feel I would have liked to take on more of the technical aspects of the project such as the work Dave did with the CPLD. While the work I did in the shop was all very necessary to the project, it did not involve much application of knowledge acquired in school. I am, however, glad to have worked with the sensor group in the debugging of the sensor sub-system as well as final integration of all sub-systems.

One thing I regret is having taken this course, ENSC 340, with so many others. I think if I were to take this course again I would dedicate an entire trimester to it. The extra hours would make the course less rushed and much more enjoyable.

Appendix A: Project Timeline - Grantt Chart