Dr. Andrew Rawicz
School of Engineering Science

Simon Fraser University
8888 University Drive
Burnaby, BC
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Re: ENSC 305/440 Post-Mortem for a Virtual Reality Bicycle Trainer

Dear Dr. Rawicz,

Enclosed is a document entitled *Post-Mortem for a Virtual Reality Bicycle Trainer*. This document outlines the process our team went through when designing and implementing our system for the V-Cycle product we are prototyping. The V-Cycle Pro is a bicycle trainer that allows the user to use their own road bicycle and train indoors in a stimulating environment during the off-season.

This post-mortem document follows the previous demonstration and presentation of our product, the V-Cycle Pro, held on April 15th, 2010. The document details the current state of the device, deviations from our original plans, and future plans for our product. It also outlines the budget constraints and time management issues we faced. Lastly we share our learning experiences, including inter-personal and technical learning.

The V-Cycle team consists of Dan Edmond, Mike Henrey, Lukas-Karim Merhi and Jack Qiao; students from the School of Engineering Science at SFU. If you have any questions, please contact Mike by email at mah3@sfu.ca.

Regards,

Lukas-Karim Merhi

Lukas-Karim Merhi
Chief Executive Officer
V-Cycle

Enclosure: *Post-Mortem for a Virtual Reality Bicycle Trainer*

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cycle

Post-Mortem

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Introduction

Our team first met in October of 2009. Throughout the fall semester, we met a number of times to discuss potential projects before deciding on a Virtual Reality Bicycle Trainer. Since January, we have been working to develop a prototype, which we demonstrated formally on April 15th. This document summarizes our learning experiences, and outlines our project's evolution over the last few months.

The Virtual Reality Bike Trainer (V-Cycle Pro) is a device that allows the user to train on their road bicycle indoors in a stimulating environment during the off-season. It retains the same degrees of freedom that a bicycle has outdoors, and provides visual and force feedback to the rider so that they can pretend to be riding outdoors. Our system will let riders train in the off-season, so that when they return to riding outdoors they will be well prepared.

Current State of the System

The system to date comprises a sound mechanical/structural system, a microcontroller interfacing with sensors, motor drivers and a PC, and virtual reality software showcasing 3D terrains.

The front lifting mechanism consists of a frame built around a linear drive system to raise and lower the front wheel with changes in terrain incline. We have coupled a DC stepper motor with a ball screw connected to the wheel platform on linear slide rails as specified in the design specification. A simple sliding counterweight system was used to overcome the weight of the rider in the linear motion system. The rear tilting linkage is built around an existing bike trainer to securely mount the rear axle of any bike into our device. The back platform employs a passive tilting mechanism with skateboard bushings and old rubber bike tubes, a simple solution to incorporate core stability into the workout.

The open-source Arduino electronics platform met the needs of our sensor interfacing and motor control. A potentiometer embedded in the bearing of the front platform that the front wheel turns on enabled the reading of handlebar turning. An accelerometer on the back platform provided fine-resolution data on the tilting of the back platform once the signal was amplified and filtered digitally. The reed switch provides reliable speed data, interfacing with an external interrupt pin on the microcontroller through de-bouncing circuitry. In line with one of our initial design goals, no sensors have been placed on the bike. The integrated PWM control of the microcontroller was interfaced with an off-the-shelf motor driver to drive the DC stepper motor. A custom serial protocol enabled communication of the microcontroller with the virtual reality software on a PC.

Virtual reality software has been implemented with open source 3D, physics, and sound engines to provide a total immersion experience for the user. This software integrates seamlessly with the serial communication to and from the micro-controller for an integrated real-time cycling experience.

Deviation of the System

Overall System

Overall there was only one major deviation from our proposed product. We originally hoped to add a system varying the resistance the user felt as they traversed up and down hills. While this was designed but never implemented, we achieved all of our other functions.

There were minor deviations within our system. These are discussed in detail below, and generally result from implementation difficulties. During our design process we had lots of theoretical plans for how certain features would be carried out, however when we began experimentation, alternate possibilities were quickly designed and implemented based on our learning.

Despite our deviations from the proposed system, we feel that our product still achieves our overall goals of making a realistic bike trainer and simulator.

Software

We made great progress with the 3d visualization software, but several large features remain as future work. The integration with Google Earth/Google Maps was not completed due to time and feasibility constraints, and the virtual terrain has been scaled back from original plans as well. While a city scene was planned, the terrain generation engine is much better at creating uneven/hilly terrains than the straight lines of a city and so the city scene was left undone. Realistic foliage and other scene props were also planned (and in fact they were implemented), but they lowered the frame rate to unacceptable levels. Further optimizations to the 3d scene, such as using level-of-detail and paging techniques may make these features feasible, but were not implemented due to time constraints.

Structural

The structural components largely stayed within original design specs, but we improvised in areas where the planned design was too difficult or expensive. While the original design called for an all-metal structure, several major components - notably the main backing plate of the front lifting mechanism - were made of or re-enforced with wood and MDF. The original design used rubber skateboard bushings for the tilting mechanism, but this proved too flexible to hold a person's weight. In addition to the bushings, several rubber tire tubes were wrapped around the frame of the bike trainer to increase the overall stiffness of the tilt mechanism.

Mechanical

For the modules that were completed, the mechanical system functionally resembled our original intent. The platform is capable of lifting and lowering the user at a reasonable speed. There are no stability concerns, with either the front platform or the tilting mechanism. The platform does not achieve the full operating range we had originally hoped for, however in terms of realism we feel the device still simulates hills well. The device is able to tilt sideways to the full 13° that we originally planned for. Our anti-gravity device contains adjustable weights, allowing the user to properly balance their mass so that the platform lifts up and down at the same rate.

However many of our implementations differed from our proposed designs. We originally proposed the use of a shock cord as an anti-gravity device (to equalize the forces the motor sees when lifting and lowering the front platform). However with experimentation it became obvious that this implementation had numerous difficulties including excessive friction forces of the cord on the pulley system we had envisioned. Instead, we implemented a counterweight system on simple linear rails. While this has the disadvantage of extra mass, and therefore the system is less transportable, it is a more conventional and simpler solution.

The side tilting mechanism originally was based around a set of skateboard truck bushings. Experimentation showed that this did not provide sufficient restorative spring force, and we applied stronger elastic force using old rubber bike tubes. The bushings remained, as the kingpin and bushing system was integral to the tilting motion – the bike tubes simply increased the spring force.

The front platform required a lot of tweaking to make it work effectively. The platform cantilever distance was increased so that the wheel had more room to rotate. A mounted bearing was selected to provide room for a potentiometer to be attached, and allow for easy wheel rotations. Aligning the motor shaft and ballscrew shaft was possibly the most difficult mechanical adjustment we made. Proper sized spacer blocks were constructed from aluminum to provide front and back alignment, and careful hole spacing was critical to ensure side-to-side alignment. None of this was envisioned in the design specification.

Microcontroller and Sensors

Our electronics hardware met all essential requirements outlined in the functional specification. Most of these specifications regarded the safety of our product. Electronics were safely enclosed in grounded metal box with proper fuses, wiring was carefully insulted for reliability and for user safety, and the high power motor driver is placed on an adequate heat-sink to ensure long-term operation of the device.

All sensors were integrated with the planned signal conditioning circuits as outlined in the design specification document. The accelerometer and potentiometer effectively sensed tilt of the back platform and turning of the front wheel respectively. The reed switch tachometer provided reliable data on speed and the limit/safety switch circuitry gave a robust mechanism for stopping the system in the event of a failure condition and initializing the elevation to a known state.

We planned initially to be able to operate the V-Cycle independently of the virtual reality software with user controls for elevation and resistance, or with a pre-loaded track. Time and budget constraints did not allow for the implementation of this feature, and it was felt that this feature would not be particularly useful without the variable resistance unit.

The communication protocol deviated slightly from the proposed design in the design specification document. To ensure a reliable data link, the serial communication protocol required error checking of ingress data via a checksum, timeouts where required, and longer ACK/ERR code words for extra redundancy.

The motor control software also deviated slightly from the proposed design. The initial design considered manipulating the PWM motor control for optimal response time. However, it was found the many cases that we considered were far too complex, and resulted in the stepper motor accumulating positional error. These errors in the motor system were particularly problematic with our open-loop motor design, and sometimes resulted in the platform moving dangerously close to its limits. The motor code was stripped down to the simplest possible system with two conditions: accumulate ingress elevation data and change directions with ingress data. This proved to be much simpler to test and verify. However, it should be noted that the problems found in the motor code after integration highlighted our need for better independent testing of the motor control subsystem. We should have run test vectors on our motor code to test all corner cases. Instead we tested the code only on the simplest of cases and found major problems after mechanical integration when the real motor control testing began.

Future Plans

Overall System

Our bike trainer has significant potential for future development. Currently we have proved the basic features of the device work properly. However work can be done improving the looks, realistic effects and usability of our product.

In terms of the overall system, here are some areas for work on the product:

- Looks of the system

  Consistency of materials and colors would improve the looks of our product. Painting the entire system, then applying our logo would be a good first step. There are instances where we have stacked pieces of metal to achieve desired thickness, or size – replacing these with single pieces of the correct size would also improve the looks.

- Usability of the system

  Our system can be difficult to use at first. It is quite highly elevated, and therefore it can be difficult for the inexperienced user to mount the bicycle. The side-to-side tilting forces could be made more realistic through the use of an active system. This would add complexity and cost, which are the main reasons we opted for a passive system; however the user would feel more realistic forces when the bike is tilting.

- Variable resistance unit

  We had planned on implementing an electronic-load, variable resistance device throughout the past 3 months, however we ran out of time. We waited too late to order one of the parts, and then it was delayed by nearly a month, arriving the day before our demo. As a result, we have designed the necessary circuitry, mounting brackets and have all the necessary parts but would still need to implement and calibrate the system. The advantage of such a system is a more realistic resistance feeling as the user cycles up and down hills.

Software

Much is left to accomplish in the visualization department. With some work, it is possible to improve the 3d graphics for a more realistic and immersive experience. A smoother User Interface (UI) would also improve the user experience - such as menus for choosing terrains and graphics options. Possible improvements include:

- Using lightmaps (a pre-calculated lighting solution) to emulate terrain lighting
- More props such as grass, trees, rocks, etc.

- LoD (level of detail) of terrain geometry and scene objects to reduce poly-count (the idea here is to use lower resolution geometry in far-away areas, and higher resolution up close, and changing the geometry as you move)
- Dynamically generated terrain using real-world heightmaps for emulation of real locations
- Tiled or paged terrain for terrains of infinite size

Because terrains are dynamically generated at run-time from a heightmap (a heightmap is a greyscale topographic image, where white = high and black = low), it is possible for the end-user to create their own terrains using an editor tool, specifying parameters like maximum elevation, terrain track geometry, and atmospheric settings. This editor tool could be developed for future work.

Other user information may also be recorded, such as the duration of the biking session, amount of work performed, heart rate, etc.

Structural

The structural components were largely constrained by budget, and for future work can be much improved, provided that a higher budget is possible. The current structural and mechanical design was conceived as a prototype, and is not suitable for mass production as a commercial product. In particular the linear motion components are very expensive and may be eliminated by using a smarter structural design. Whereas our system is held together using fasteners, a welded space frame would be cheaper and much more durable. The tilting mechanism in particular needs to be improved - while tire tubes are quite effective and inexpensive, they are rather unsightly and would not be suitable for a commercial product. Similar problems exist for the counterweights - a better design is to use springs or elastic, which would reduce the overall size and weight of the device. Ideally, the entire mechanism would be portable, so that it can be transported in an average-sized vehicle.

Mechanical

The mechanical system has a couple aspects that could be improved. These are listed below:

- Noise reduction

  Audible noise is a concern with our device. With a virtual reality system, ideally all the sound should be realistic cycling sounds, and the user should not notice system or motor sounds. Damping the noise could be accomplished in a couple ways; first the user could wear noise-cancellation headphones. Alternately, or in conjunction, the motors could be mounted on damping rubber bushings to reduce vibration and noise.

- Wider band of realistic motion frequencies

  While our system design is quite appropriate for handling low frequency up and down movements, it could never respond fast enough to simulate the difference between riding on gravel vs. asphalt.

To provide a higher range of operating frequencies, silent, speaker-type devices could be attached to our system. These would vibrate at the required frequencies and the user would feel as though they were bouncing along an uneven road. These devices exist, and are designed specifically for use in virtual reality systems.

Microcontroller and Sensors

It should be noted that since we dedicated the microcontroller serial interface for transferring sensor and motor control data to/from the virtual reality software and the microcontroller, we had no provision for getting debug information from the microcontroller during operation with the virtual reality software. This made microcontroller software errors encountered in the integrated system almost impossible to source. To reduce the frustration associated with this, the serial communication protocol should include a provision for transferring debug information, or we should set up a different communication interface for debugging entirely.

In the future, we would like to be able to operate the device in stand-alone mode as dictated by the function specification (part of the motivation behind using a microcontroller in the design and not just a PC). This would require building a simple user interface for use with the microcontroller.

Budgetary and Time Constraints

Budget

Table 1 contains the budgeted cost and the actual cost of the project up to April 15th, 2010.

Table 1: Budgeted and Realized Costs of V-Cycle Pro

Required Materials	Realized ($)	Budgeted ($)
Electronics Components	**479.02**	**465.00**
Sensors and analog circuitry	234.02	130.00
Digital circuitry	245.00	335.00
Electro-Mechanical Components	**990.88**	**630.00**
Structural (Metals, struts, wood, fasteners)	409.52	100.00
Mechanical (Ball screw, linear actuators, motor, power supply, generator)	376.69	380.00
Bike trainer	204.67	150.00
Total	**1469.90**	**1095.00**

The budget estimated for the structural category was a lot less because we underestimated the cost of components, such as metal, struts, wood, and fasteners. This was expected since none of the team members were mechanical or structural engineers. Under the realized digital circuitry, we included a fried G251 motor driver that cost $100 with shipping therefore unfortunately increasing our realized costs total.

We were able to receive $650 form the ESSEF (Engineering Student Society Endowment Fund). Since our design did not include any wireless components, we were unable to qualify for any of the IEEE grants for senior engineering projects. The remaining costs of the project were totally member funded.

Time Constraints

Table 2 contains our proposed milestones dates and when they were actually implemented.

Table 2: Development Timeline

Item	Proposed	Implemented
Order parts	February 3	Ongoing
Sensors	February 5	March 9
Front lift platform	February 19	April 1
Resistance electronics	February 23	Not implemented
Tilting system	February 26	March 1
Stepper code	March 6	April 14
Resistance mechanical	March 12	Not implemented
2D acceleration	March 23	March 22

It was expected that we would not be able to accomplish most of the milestones on time. Most were actually implemented 2 weeks to a month after the set dates. We especially underestimated the complexity of stepper code, structural and mechanical implementation of the front and back platform.

Even though we almost did not meet any of the scheduled dates, having milestones kept us in check and pressured us to persist especially since we were among the first groups to demo on April 15th, 2010.

In the last 2 weeks before the demo, we accumulated many nights without sleep to assure that our product was reliable, safe, functioning, and in the end we were able to achieve all three.

Interpersonal and Technical Experiences

Dan Edmond

I have been privileged in the last 3 months to work with such a high energy, high performing group of people.

What impressed me most about our group was our ability to write the design specification, fully understand the design constraints of our respective subsystems, and communicate effectively during the design process to ensure smooth integration of the subsystems. I remember one day in particular after months of working independently on our subsystems where we had essentially only just hooked up the entire system and were able to see our cycling avatar on the screen move in real time.

The V-Cycle Pro gave me valuable exposure to mechanical design, and incredible experience with programming real time systems. My best lesson learned is to design all systems for testability. Neglecting this requirement created much last-minute frustration debugging motor control code which I never wish to repeat. I will always consider the testing of a system in its design in the future.

In the last month, it seemed that we had the best people working on what they had to in order to finalize integration and get the device working on time. I was always confident that the V-Cycle would work as we intended it to for the deadline, and it did. I thoroughly enjoyed working with the group throughout the entire development phase. We always gave and accepted honest and critical feedback between ourselves on design decisions, never fighting because we recognized that open and honest communication would build trust in the group and result in a better overall product. It is largely for this reason that I would work with this group on future products.

Furthermore, as the cyclist in the group, I can say with conviction that we effectively created a product that makes indoor cycling fun and engaging!

Jack Qiao

I feel that since the beginning we've had good team dynamics, everyone pulled their weight and things just got done. The weekly meetings, which helped flesh out ideas and courses of action, helped a lot in the planning and were an invaluable tool.

I've learned that decisions made at the beginning of the project can have a large impact on the overall direction of the project, and should be made with heavy consideration. In particular the choice of 3d engine in the beginning of the project had a great impact on the features that were possible. We switched from the Irrlicht engine to Ogre 3D in the middle of the project to take advantage of easier physics integration, resulting in much wasted effort. More planning also should have been given to acquiring proper tools for metal working, especially a drill press. Many more possibilities would have been available mechanically had we had the right facilities, such as welding equipment, a milling machine, and a lathe. I did learn a lot about working with metal, and found great places to buy materials in the future.

Time was also a huge issue. If we had two semesters to work, a much more complete project may have been possible. However, I'm not certain that our interest or motivation would last through two full semesters of working on the same project.

Lukas-Karim Merhi

In the past 13 weeks, my team and I spent almost every day working on V-Cycle Pro in my living room. The project slowly took over all aspects of our lives. At the beginning of this endeavor, my intention was to learn as much as I could from all aspects of the projects, and surely I succeeded. In addition, I wanted the project development stage to be as much fun as possible; that turned out not to be always the case.

With regards to technical experience, this project was an enormous learning experience. Firstly, I had never used an Arduino microcontroller before, and it turned out to be a great development tool especially with its open source platform, multiple analog and digital pins, serial communication, and headers for attaching custom made prototyping boards. Secondly, throughout my undergraduate degree I never had to work on any structural or mechanical design projects and this was the first time I had the opportunity to do so. It was a frustrating experience sometimes because one needs a lot of patience since mechanical and structural design implementation requires the proper tools, proper materials, and most importantly precise measurements. At the end, those requirements paid off greatly because it resulted in a reliable, safe, and functional product.

One of the greatest highlights for me during this semester was working with the team since we are all really good friends and worked well together. It was an asset to know that they were reliable, hard-working, and trust-worthy. Everyone always delivered on their parts and was always available if someone needed a second hand in doing something with the project.

As always, a technical project like this one could have been done in many different ways, and we periodically voiced different opinions of how to achieve this. But we always agreed that we would pursue the most practical, modular, and lowest cost option. We were also careful not to shut down anyone ideas and be open to criticism from the start. In addition, we had at least one meeting per week to revise goals and milestones. This kind of environment allowed for great team dynamics.

Lastly, I learned to always ask if I didn’t understand something and that making mistakes are essential to any learning experience.

Mike Henrey

At the start of the semester I set a few goals for myself with regards to 440:

1. Have a fun 440 project, and do something that I will be proud of,
2. Not write a single line of code, and
3. Be able to demo and show something off to friends and family

With regards to goal 1, I feel quite satisfied. We decided from the beginning that we would not settle for a 'lame' project. Jack and I were quite interested from the start in a project that could be posted on a web blog and linked to websites like hack-a-day, and I still feel that once we sort out all our design notes and pictures that achieving internet notoriety is quite possible.

But fun extends past simply the end product (which is still in Lukas and Dan's living room and still gets tested by visitors). We worked well as a team: we took the time to watch hockey games together during the Olympics and go to parties throughout the semester. In terms of candy, it was determined that Wine Gums are superior "440 candy" than either jelly beans or jujubes.

My second goal requires little discussion. Our project had plenty of mechanical aspects, and I achieved this perfectly. I learned lots about working with metal, from where it is sold in Burnaby to what tools can be used with it. There were frequent opportunities for me to exercise my creativity, from merging our device with a skateboard to allow for side-to-side tilting, to finding a way to bend sheet metal without a press brake. I learned a lot more about design and construction techniques from experimentation than I could ever learn from courses in school.

My third goal stems from the fact that I have seen a few 440 demos and was always disappointed. It seems that students work for hundreds of hours on their projects and then demo in a room with a couple friends, the instructors and a closed door. It seemed depressing to me that you can spend 5 years of your life in an engineering program, and no one cares what you have accomplished at the end of it.

The response we got to our preview videos was fantastic. I wish that we had thought of that earlier, in fact keeping a blog with constantly updated project information would have been great. I was blown away by how many friends and family we all had at our demonstration, and by how impressed everyone who attended was. Our project was easy to show off and many people appreciated that they could try it out.

All things considered, the project was hugely successful. At the start of the semester we had a fun idea, and by the end we had a functioning prototype and functioning team. Each team member was able to contribute in a manner that worked for them and leveraged their unique skills. The project was well matched to our team, and this was why we were able to accomplish so much.