The development of underwater robotic vehicles throughout the past 30 years has contributed significantly to various types of underwater search, survey, and recovery applications. To learn about these complex systems, the MIT Design of Ocean Systems Class of 1997 designed and built an inexpensive Autonomous Underwater Vehicle (AUV), Autolycus. The Design Class of 1998 further developed this vehicle, adding a sonar altimeter to its sensor array, as well as integrating a dead reckoning navigation system. In the spring of 1999, the design class was challenged to modify the AUV Autolycus to incorporate environment-based control and to double the vehicle’s maximum controllable velocity. To succeed in these modifications, a thorough understanding of state-of-the-art AUV systems, design of new hardware and software systems, and extensive testing and evaluation of these systems were required. Results of these efforts included the addition of a five-channel sonar system, new main thrusters, and a new control algorithm used to control the new hardware. Preliminary successes in wall-following and other environment-triggered behaviors were achieved.

Introduction

AUTONOMOUS UNDERWATER VEHICLES (AUVs) have rapidly gained popularity throughout the marine industry over the past ten years due to their wide range of applications in areas such as: oceanography, naval defense, and salvage [1]. AUVs are also particularly useful teaching tools because they incorporate many common ocean systems in a small, accessible package. In 1997, a group of students from the Massachusetts Institute of Technology designed and constructed the AUV Autolycus. Autolycus was built to be used as an educational tool for undergraduate students in the Department of Ocean Engineering at MIT [2]. The advancements made to Autolycus that will be discussed herein were made in the context of a two-semester course series entitled Design of Ocean Systems I & II. All work was done by a four-student team comprising the Design Class of 1999. The first semester was devoted to learning
about the vehicle's existing systems and formulating a comprehensive report detailing proposed designs and modifications to the vehicle [3]. The second term was dedicated to the construction, integration, and testing of these modifications [4].

History and future of AUVs

As the capabilities and versatility of AUVs have developed, the use of these vehicles has sparked a new age of ocean survey and exploration. AUVs are being used to replace human divers, manned submersibles, and remotely operated vehicles (ROVs) for a variety of reasons including lower operating cost, removal of human danger, and maneuverability [5]. AUVs are being designed and constructed for oceanographic studies of the deepest and harshest of underwater environments. The Woods Hole Oceanographic Institution (WHOI) has developed the Autonomous Benthic Explorer (ABE), which was designed for long-term deployment and benthic monitoring [6]. This vehicle has been employed for oceanographic surveys of the Juan de Fuca Ridge in the North Pacific Ocean [7]. The MIT Sea Grant College Program has developed a number of AUVs, including the current Odyssey IIb. Odyssey class AUVs have been used for a variety of missions such as studies of water mixing in the Haro Strait, near Vancouver, British Columbia. In these missions, the AUVs carried sensor suites for measuring water quality, current profiling, and a side-scan sonar [8]. MIT Sea Grant is currently developing a new class of AUVs, ALTEX, designed for Arctic Basin surveying. These vehicles will have a range of 1000 km, an operating depth of up to 4500 m, the capability of operating autonomously for up to two weeks, and data transmission systems capable of melting through the ice and transmitting data via satellite [9].

AUVs are also useful academic tools because they offer relatively easy access to small-scale examples of many ocean engineering topics including hydrodynamics, propulsion, navigation, and electronic systems. This makes AUVs perfect tools for student-based design and research.

History of Autolycus

Autolycus was originally built by the Ocean Systems Design Class of 1997. The goals at this time were to produce a small, easily adaptable vehicle, capable of precise maneuvering and positioning at speeds up to 0.5 m/s [2].

Upon its completion in the Fall of 1997, Autolycus was capable of controlling its depth and pitch. A compass and speed sensor had been physically integrated into the vehicle, but were not capable of operation. Forward motion was open-loop and the maximum observed speed was 0.35 m/s [2].

The Design Class of 1998 made huge advancements in the horizontal motion of the vehicle. The compass and a newly designed speed sensor were integrated into the software, allowing closed-loop forward motion. Unfortunately, the compass readings were inaccurate in the vehicle’s operating environment of the MIT swimming pool due to the pool’s varying magnetic field. In the vertical direction, the addition of an altimeter (downward-looking sonar) enabled the vehicle to control its distance from the bottom. Unfortunately, the pressure sensor failed, resulting in the removal of the sensor and its control software from the vehicle [10]. Due to the modifications made by the Class of 1998, the drag of the vehicle increased, decreasing its maximum speed to 0.24 m/s [3].

Table 1 is a summary of the history of Autolycus’s sensor array, the hardware and software that was constructed in 1997, and changed in 1998.

### Table 1 Autolycus sensor suite 1997–1998

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Hardware</th>
<th>Software</th>
<th>Functional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyroscope</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Inclinometer</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Compass</td>
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<tr>
<td>Speed sensor</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Altimeter</td>
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<tr>
<td>Range sensors</td>
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</table>

Objectives

Based upon the uses of AUVs and the state of Autolycus at the end of 1998, the objectives of the Design Class of 1999 were:

- **Environment-based control**—It is vital for an AUV to be aware of and respond to its surroundings to prevent collisions and to survey both natural and manmade objects. Sonar units were to be used to measure the distances to objects in various directions and new control algorithms were necessary that would make the vehicle respond to these measurements.
- **Increased maximum controllable speed**—The maximum speed of 0.24 m/s greatly limited the vehicle's range of applications. Achieving a speed of 0.5 m/s would significantly enhance Autolycus’s versatility. New, more powerful motors as well as larger propellers were to be used to achieve this speed increase.

Design and modifications

Structure

The body of Autolycus (Fig. 1) is a cylinder 1.3 m long, composed of three main sections: forward, pressure housing, and aft. The forward section consists of a vertical thruster (3a), an altimeter (1), a forward-facing sonar transducer (4a), starboard and port side-facing transducer (4b), and a housing for “wet” sensors (2). The pressure housing contains the onboard computer, “dry” sensors, electronics, and batteries (6). The aft section consists of a second vertical thruster (3b), two horizontal thrusters (5), and starboard and port side-facing transducers (4b). The Class of 1999 modified the thrusters and integrated all of the sonar transducers, except the altimeter, into Autolycus.

Propulsion

The original motors were Micro Mo Series 1331 DC brushed motors, capable of a two watt output [11]. With two of these motors and 3.5 in. (8.9 cm) brass propellers, Autolycus was capable of speeds up to 0.24 m/s. These motors were selected for their reliability, efficiency, and small size [2]. The motors were run open-loop, so actual speeds differed due to
variances in motors and shaft seals. They were housed in form-fitting Delrin cylinders with press-fit, O-ring sealed ends. These housings were extremely small, thus creating little drag; however, they were difficult to open for motor repairs.

In order to double the speed, the overall power output needed to be increased by a factor of eight. Since more powerful motors are larger, the total drag of the vehicle would also increase; thus more powerful motors would offset some of their own advantage. Due to a high power to size ratio, as well as reliability and availability, Micro Mo Series 3557 CS “Super” DC brushed motors, capable of outputs of up to 20 watts were selected as the new motors [11]; matching gearboxes and encoders for the new motors were also obtained. This selection was based on the worst case scenario that better propellers could not be obtained. These motors necessitated the design and construction of new housings, which were made of Delrin. The shaft seals in the housings are commercially available shaft seals for low friction and are more evenly matched than the original O-ring seals. The housings are capped with O-ring sealed, clear Lexan covers allowing easy visual inspection for leaks and loose connections. An additional improvement came in controlling the motors. Commercial motor controllers, made by J. R. Kerr, were used which enabled extremely accurate closed-loop motor control [12]. Additionally, these controllers performed all of this control internally, reducing the central computer’s computation time. The final improvement to the propulsion came in the use of APC 10 × 6 model airplane propellers. These are two-bladed with a diameter of 9 in. In its final configuration, Autolycus’s maximum sustained controllable speeds exceeded 0.5 m/s.

Power

The previous battery system consisted of eight alkaline D-cells in parallel with two rows of eight alkaline AA-cells, resulting in a 12 volt system. With the addition of more powerful motors, the load was so large that the voltage quickly dropped below the cut-off voltage of the power amplifiers in the motor controllers, causing frequent motor failures. The battery section of the vehicle, located in the bottom of the pressure housing, now houses three rows of nine D-cells. Terminals were mounted on each bulkhead and the hull itself was used to hold the batteries in place. This new battery system resulted in 2.5 times the available power. It also boosted the electrical system from 12 to 13.5 volts, allowing larger voltage drops before electronics would shut off. It was estimated that the vehicle could run continuously with all four motors at maximum speed for one hour. In practice, after implementing the new battery system, the vehicle could run for one day’s testing (noncontinuously) on one set of batteries, without any problems due to sagging voltages.

Electronics

Computer—A Tattletale Model 8 (TT8) microcomputer controls Autolycus. The TT8, manufactured by the Onset Computer Corporation, is a specialized computer designed for machine control and data logging [13]. It is compact, efficient, and powerful. Peripheral Issues’ Persistor CF8 Compact-Flash card is used for storing up to 15 megabytes of data, which is logged and processed by the TT8 [13]. The vehicle acquires data at a rate of two hertz and stores it on the flashcard for post-mission processing. The vehicle’s control software is written in C, and has been developed by each Design Class on a PC using Aztec C.

Sensors—At the end of 1998, the sensor suite of Autolycus was insufficient if the vehicle was to be used as an environment-sensitive robot. Autolycus was equipped with a working gyroscope, inclinometer, and altimeter. It also possessed a pressure sensor, speed sensor, and compass; however, they did not work properly and needed to be repaired or replaced if they were to be used. Table 2 is a summary of Autolycus’s sensors and their functionality at the end of 1998 and 1999.

The following is a description of each of Autolycus’s onboard sensors, their state in the Spring of 1999, and modifications that were made, if needed, to the sensors that were used.

Table 2 Autolycus sensor suite 1998–1999

<table>
<thead>
<tr>
<th>Sensor</th>
<th>1998</th>
<th>1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyroscope</td>
<td>X</td>
<td></td>
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<tr>
<td>Inclinometer</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Compass</td>
<td>X</td>
<td></td>
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<tr>
<td>Speed sensor</td>
<td>X</td>
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<tr>
<td>Altimeter</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Range sensors</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 2 Autolycus sensor suite 1998–1999
Gyroscope—The gyroscope measures yaw rate. Integrated, this value yields the relative heading of the vehicle. Use of the gyro for long-term navigation was unreliable because its measured values possessed a significant, uncharacterized drift that resulted in inaccurate heading measurements. Through empirical testing, the range of the error of the gyro was determined and compensated for in the software, minimizing the error in measurements and allowing its use for navigation over short intervals of time.

Inclinometer—The inclinometer measures the pitch angle of the vehicle. The inclinometer was fully functional and accurate at the beginning of this project.

Pressure sensor—This sensor measures the water pressure surrounding the vehicle, which is used to calculate depth. The hardware of this sensor was damaged in 1998, and the software was removed. In 1999, new hardware and software were added, calibrated, and used with the inclinometer to achieve closed-loop depth and pitch control. The range is zero to 30 ft deep.

Compass—The compass measures the heading of the vehicle. This sensor worked well on the bench; however, when it was used in the pool, it gave inaccurate readings. This is due to the complex magnetic field created by the steel surrounding the pool. The vehicle was capable of following a heading; however, the compass readings were not consistent within the pool, and therefore unreliable for precise heading control. This sensor was not used for navigational control during this project.

Speed sensor—A speed sensor measures horizontal vehicle speed. Both the Classes of 1997 and 1998 attempted to integrate a speed sensor into Autolycus. The first attempt, a paddle wheel sensor, had a range that was too high for the speeds that Autolycus was able to operate at. The Class of 1998 added a propeller-type speed sensor on the front of the vehicle. This sensor was removed in the Spring of 1999 because it had corroded and was no longer operational; also, a sonar transducer was to be mounted on the nose of the vehicle. Ultimately, a speed sensor was not used for the project.

Altimeter—The altimeter is a sonar unit which is directed vertically downward. It emits an acoustic 500 kHz signal, called a “ping,” and measures the time it takes for the signal to return. This measurement is converted to measure the altitude of the vehicle [10].

Range sensors—To be able to sense the side and forward walls of the pool, Autolycus needed a sonar system. Five sonar transducers were incorporated into the vehicle, one facing forward and two facing out from each side.

Hardware—The transducers and sonar controller board were modified from the Speedtech Depthmate Model SM-5As, handheld acoustic depth finders which operate on a 9 Volt battery at a frequency of 200 kHz and have a 24 deg beam angle. Its theoretical range is 0.6 to 79 m [14]. Experimentally, the consistent range was 0.1 to 4 m in the pool, although measurements of up to 5 m were obtained. The Depthmates were chosen because they were inexpensive and easy to modify. Five Depthmates were purchased, modified, and used for Autolycus’s heading and wall-following capabilities.

Mounting—Three transducers were mounted on the front of the vehicle, one facing forward, one to port, and one to starboard. The forward facing sonar is bolted to the front of the vehicle. The forward side-looking transducers are located in the vertical thruster section. Two were mounted in the rear, one facing port and one starboard. The aft transducers are attached to L-brackets which are bolted to the front of each horizontal motor housing.

Electronics—The electronic components of the sonar circuit are: the TT8, a 6811 microcontroller board, the sonar controller board from the Depthmate, a relay addressing circuit, and the transducers. The 6811 is the microcontroller that is used for controlling the new five-channel sonar system. It is used as the intermediary between the TT8 and the sonar board taken from the Depthmates. This system operates as follows:

The relay addressing circuit closes the connection between sonar controller board and the commanded transducer; this arrangement allows only one transducer to “ping” at one time, preventing the chance of acoustic interference. The 6811 tells the relay circuit which of the five transducers is to be used; the transducer pings. The 6811 gives the TT8 two values: the time at which the commanded transducer pings, and the time when the returned signal is received [4]. With these two times, the TT8 is able to calculate the distance from the vehicle to surrounding objects.

Software

Software structure—The final version of the vehicle software used by the Class of 1998 followed the structure as illustrated in Fig. 2.

Missions were broken up into a number of legs specified by the user. The user then entered the following parameters for each leg: time, altitude, pitch, heading, and speed. For each leg, Autolycus would try to maintain each of the parameters until the commanded time had elapsed, at which point the next leg would be triggered. Throughout the mission, all sensor data and thruster commands were stored in an array at a rate of two hertz. Upon completion of all legs, the thrusters were commanded to stop, the array of data were saved on the flashcard, and the program exited.

The structure of the final version of the vehicle software used by the Class of 1999 was similar, but contained a few fundamental changes. Missions now consisted of two types of legs, straight and turning. Each of these legs requires a different set of parameters, as illustrated in Table 3.

The end of each leg was triggered by events rather than time; straight legs were ended by the vehicle reaching a commanded distance from an object in front of the vehicle; turning legs were ended by an integrated gyro reading indicating that the vehicle had turned through a commanded angle. These two types of legs are the fundamental building blocks that can be used to create nearly any desired mission profile. The other significant change occurred in data logging. The addition of three sonar readings and the new control algorithm resulted in creating such a large data array that it surpassed the RAM capacity of the TT8. To fix this, data were...
logged every control cycle with only the last five data sets saved in RAM; this did, however, drastically increase the duration of the control cycle. These five data sets were necessary for the control algorithm. Figure 3 shows the current code structure, illustrating the difference in the method for data logging.

Control algorithm—The control algorithm created by the Class of 1999 consisted of two functions within the software; regardless of the type of leg (straight or turning) both were called. The first function is used to calculate the vehicle’s current heading and desired heading. Figure 4 depicts the progression of a typical straight leg.

In a straight leg, the current heading is measured relative to a wall on the side of the vehicle. The current heading is calculated using simple trigonometry, the difference in the readings from the two sonars, and their spacing on the vehicle. The commanded heading on straight legs is set to be 0 deg, creating a desired trajectory that is parallel to the wall. The distance to the side wall is also calculated; it is simply an average of the two side-facing sonar measurements. If the distance to the wall is not the commanded distance, the commanded heading is altered to one that will aim the vehicle back toward the desired trajectory. The size of this heading deviation is proportional to the error between the commanded and current distance from the wall.

Figure 5 depicts the desired trajectory (1), Autolyces at an incorrect distance from the wall, and the path the vehicle would follow to achieve a 0 deg heading at a commanded distance from the wall (2).

In turning legs, the current heading is found by integrating the gyro readings throughout the turn, and the commanded heading is set to be the turn angle commanded by the user during initialization. A turning leg is illustrated in Fig. 6.

The next function is responsible for using these headings, as well as other sensor data to generate thruster commands that will move the vehicle as commanded by the operator. These values are proportional to the errors between the current heading, pitch, and depth values and their commanded values. In the case of depth and pitch, derivative error values are also used for better accuracy. Once these errors are found, they are then scaled by individual, empirically-determined gains. The previous thruster values are then updated by these scaled values to produce the new thruster commands.

The last step in either type of leg is to command the thrusters with these updated values.

<table>
<thead>
<tr>
<th>Mission leg parameters</th>
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</thead>
<tbody>
<tr>
<td>Straight</td>
<td>Turning</td>
</tr>
<tr>
<td>Depth</td>
<td>Depth</td>
</tr>
<tr>
<td>Distance to side wall</td>
<td>Port motor speed</td>
</tr>
<tr>
<td>Port motor speed</td>
<td>Sbd motor speed</td>
</tr>
<tr>
<td>Sbd motor direction</td>
<td>Port motor direction</td>
</tr>
<tr>
<td>Port motor direction</td>
<td>Sbd motor direction</td>
</tr>
<tr>
<td>Distance to forward wall</td>
<td>Turn angle</td>
</tr>
</tbody>
</table>

Fig. 3 Software structure in 1999

Fig. 4 Straight leg progression

Fig. 5 Heading control
Field testing and vehicle performance

Field testing

Field testing was accomplished both in and out of the water. The following is a summary of the tests that were conducted in the order and facility in which they were performed.

Before wet testing, experiments addressing thruster and sonar functionality, and gyro and inclinometer calibration were conducted on the bench. The Marine Computation and Instrumentation Laboratory testing tank (MCIL) was an excellent facility for testing all hardware, including the pressure sensor, inclinometer, gyro, sonar, and motors. Missions which integrated all of these systems, using their control algorithms were tested independently and then added together to achieve multiple leg missions. Due to its small size (4 × 8 m), the MCIL was insufficient for testing the wall-following control algorithm. The MIT Alumni Pool provided a long enough distance (23 m) to properly experiment with the control gains for wall following.

Vehicle performance

Dry and wet tests were conducted, as outlined in Table 4. The following are descriptions of the performance of the vehicle as well as data plots from missions conducted during the exhaustive testing in the Fall of 1999.

Speed—The modified thrusters increased the speed of the vehicle considerably from a mere 0.24 m/s to a maximum greater than 0.8 m/s. With heading and wall-following control, the maximum speed of the vehicle is over 0.5 m/s.

Depth and pitch control—The new pressure sensor is extremely accurate. When used in conjunction with the inclinometer and vertical thrusters, the vehicle is able to achieve precise depth and pitch control. Figure 7 shows Autolyxus's depth and pitch as the vehicle descended from a depth of 0 m to its commanded depth of 2 m, while moving forward.

It reached the commanded depth in 17 sec, after which the pitch stabilized to its commanded 0 deg. The vehicle maintained a 2-m depth and 0 deg pitch throughout the remainder of this mission.

Heading control—The drift of the measured gyroscope readings was characterized during bench tests and compensated for in the software, but it still could not be used for long periods during a mission because of residual drift. This sensor was used for measuring the heading of the vehicle during turns, which were short enough that the error did not have a large effect on the measured heading. A turn leg terminated when the vehicle reached a commanded angle.

Testing determined that the ideal end angle for a 90 deg
turn was 67 deg; momentum would carry the vehicle through the remaining 23 deg. The heading measured by the gyroscope during a turn leg is shown in Fig. 8; the leg ended soon after it reached 67 deg.

The newly integrated sonar system worked very well for short ranges; measurements reached a maximum of 5 m, but were reliable only to 4. When it was within this range, the forward-facing sonar was used to trigger the end of a straight leg. Due to occasional sporadic readings, an outlier rejection algorithm was added to the software; this triggered the end of a leg only when five consecutive readings were within the commanded distance. These readings were made every control cycle, so this did not radically decrease the response time.

The side-facing sonars were used to measure the distance to the side wall. These five readings were used to calculate the heading of the vehicle during a straight leg and for maintaining a commanded distance from an object, in this case, the side wall of the pool.

Figure 9 depicts the heading of Autolycus during a straight leg. The commanded heading was 0 deg. When it reached 35 sec, the vehicle was hit by a “jet” pumping water into the pool. This jet pushed Autolycus off of its 0 deg heading, but as the figure shows, it realized the course had changed and moved to compensate for it.

Wall following—The last application of the side sonar measurements was for wall following. The distance from the side wall is plotted in Fig. 10.

At the beginning of this mission, Autolycus was placed at a distance of 0.5 m from the side wall; the vehicle attempted to reach the commanded distance of 1 m. It ultimately does not quite attain it, but comes within 10 cm. Further refinement of empirically determined gains should improve the vehicle’s wall-following abilities. Results are promising for future use of the new sonar system and control algorithms in environment-sensitive navigations.

Conclusions and recommendations for future work

The performance of Autolycus must be examined in regards to the objectives laid out initially, which were based upon both the current uses of AUVs and the state of Autolycus in the Spring of 1999:

- environment based control
- increase maximum speed

Environment-based control was achieved. The control could be fine tuned and better characterized through slightly more testing; however, testing to date has proven the physical systems, as well as the control algorithms, to be both accurate and successful in design and implementation. Autolycus’s overall capabilities have been greatly enhanced, moving it into the ranks of a “smart” robot.

The second objective, to increase the maximum speed, has also been accomplished. Even with the additional constraints...
on motion, the vehicle has still surpassed the goal of 0.5 m/s. In addition to the speed increase, the motors can now be controlled more accurately, another factor contributing to the overall improvement of the vehicle maneuvering, one of the original goals of the Class of 1997.

Through the work done by the Class of 1999, the duration of the main control cycle of the vehicle has been greatly increased, thus decreasing the reaction time. To combat this, an additional TT8 could be used. This TT8 could be used for data logging (the longest single step in the cycle) or data processing, or to just perform some of the current TT8’s tasks. Physical, electronic, and software integration would not be extremely difficult due to space in the pressure housing and the versatility of the TT8s.

More precise stationkeeping and maneuverability could be achieved by adding another set of thrusters that would act in the sway/yaw plane. These would allow Autolycus to maintain these two criteria as easily and accurately as pitch and depth are currently controlled. Additionally, these could be used for steering, thus allowing the present port and starboard thrusters for forward (or reverse) motion only, further increasing the speed.

Finally, the drag of the vehicle has grown with each year. This is an issue that needs to be addressed as it has grown to the point where these changes contribute greatly to the overall vehicle drag.

Any of these items would be useful areas for future Design of Ocean Systems classes to address in the evolution of Autolycus.

Acknowledgments

Support for this endeavor was provided by the MIT Department of Ocean Engineering. Many thanks to our classmates, Reginald Green, II and Stacie Wu, and our instructors Dr. Thomas Consi and Prof. John Leonard. We would also like to thank Prof. Chryssostomos Chryssostomidis, Prof. Jerome Milgram, Rich Kimball, Lindsay Price, Asa Prentice, Stephanie Chen, and all the past 13.017 and 13.018 students for their inspiration, time, and encouragement.

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