Tracking an Underwater Target

by

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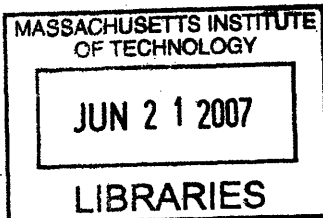MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Abstract

Autonomous underwater vehicles are becoming an important part in marine research. In order to help bring down the cost of running a research mission with an autonomous underwater vehicle (AUV), the method of tracking the AUV can be improved. An autonomous surface vessel (ASV), equipped with both acoustic instrumentation and wireless or radio communication technology, can successfully track the AUV and interface with scientists. An ASV named RoBoat, built at MIT in undergraduate classes using a kayak hull, is vessel that can be controlled remotely. To help RoBoat become fully autonomous, a program must be created to take in the data from the underwater acoustic sensors and output commands that the kayak can follow.

This thesis studies the homing rules that govern the kayak, under realistic tracking scenarios. The kayak dynamics were modeled and the response to several AUV paths was simulated. The simulation uses many of the kayak properties to be able to create a model that can be used with this specific ASV. The AUV is modeled as a single point target and follows four different common trajectories: a straight line, a line with a delayed start, a simple turn and a lawnmower configuration. There were several quantities varied throughout these four cases in order to understand more about the nature of the model; these quantities are the speed of the vehicles, the thrust control gain, the heading control gains and in the lawnmower case the distance between a turn around.

With this controller, the kayak responded in predictable ways. An decrease in speed and an increase in the thrust control gain will both lead to smaller trailing distance. Both quantities had large effects on the response and path of the kayak. The heading control gains had very little effect in any of the situations. When the kayak encounters sharp turns, it can overshoot the target path, but will settle within fifty seconds. Within these scenarios encountered, the kayak did not fail its mission; the kayak always stabilizes to a reasonable path.

Table of Contents

Introduction

In the world of marine technology and exploration, autonomous underwater vehicles (AUV) are being used in increasing numbers for ever expanding roles. From oceanography and surveying , to study marine life and the expanses of the sea, to inspection. AUVs are often, used to examine underwater piping and other underwater structures. AUVs have become popular because they keep the cost of the mission down. While it is expensive to design and build an AUV, losing an AUV is not the same as losing a human life. Keeping humans out of danger is a key advantage to AUVs. In getting humans out of the vehicle, the design also changes in that the safety factors can come down, because all you are protecting is equipment. The use of AUVs is a critical part of marine research.

AUVs only become cost attractive when they are truly autonomous. In tracking an autonomous underwater vehicle, human involvement becomes very costly due to the need to take a large research vessel out to the research site. This large vessel must house the scientists, transport and track the AUV, and must be supported by a crew. After successful deployment of the AUV on its mission, there is no reason to spend thousands of dollars to have the ship track the AUV. Yet, AUVs can make errors; they do need to be tracked in case anything goes wrong. Other reasons for tracking and communicating with AUVs is the ability to change the mission en route or to download data immediately. Bot of these capabilities can be very useful in certain missions. One proposed solution is an autonomous surface vessel that communicates with the AUV acoustically and with the rest of the world via wireless.

In the spring of 2005, work began to construct a vessel based on the idea that a small boat could do the job of a costly ship. The small boat could communicate via sonar to the AUV and via wireless signals with the researchers. While radio and satellite communication can traverse long distances and remain clear, only acoustic signals can be read clearly underwater. The vision was an autonomous surface vessel (ASV) that would track the AUV and serve as a link for communication from the researchers to the AUV. By the fall of 2006, the task was well underway, using the hull of a kayak. In December of 2006, most of the subsystems had been successfully integrated into a working surface vessel - RoBoat. RoBoat was a fully-functional surface vessel that could be controlled remotely via wireless communication. Given a heading and a value for thrust, the kayak proved to be reliably maneuverable. While the acoustic tracking system was not ready to be mounted on the kayak, the system proved to be a success as a tracking tool. With the boat running but not yet tracking autonomously, my colleague James Sannino and I chose to finish the task as our senior thesis/project. James worked on improving the acoustic tracking system and I worked on the program that would interpret the data from the acoustic signals and output signals to the vessel controls of RoBoat.

Due to time constraints the program became more of a simulation of the response of the kayak to hypothetical AUV trajectories. With this simulation, we can study the homing rules for the kayak under realistic tracking scenarios.

Background/Theory

My final product is a code that simulates the response of a model of the kayak given a target path. The model to fit the dynamics of a kayak involves five critical variables, namely, the velocity of the kayak, the angle of the direction of the kayak's motion, the rate of change of this angle and x and y position of the kayak. These variables appear in different characteristic equations for the kayaks motion.

The first equation to model the kayak comes from a force balance where

$$\sum F = ma \quad . \tag{1}$$

The forces acting on the kayak are due to the thrust of the motor and the drag from the water. To put the acceleration in terms that will relate to other equations more easily, a can be written as the derivative of the velocity. These considerations yield

$$m \dot{u}_k = T \cos\varphi - \frac{1}{2} C_D A_w \rho u_k^2 \quad , \tag{2}$$

where m is the mass of the kayak, u_k is the velocity of the kayak, T is the thrust from the motor, φ is the angle of the motor, C_D is the coefficient of drag for the kayak, A_w is the wetted area, and ρ is the density of water. The mass of the kayak is 95.28 kilograms; this value is taken as the mass of the kayak plus all of its technical components. The density of water is taken as 1000 kg/m^3.

The cosine in the thrust term is due to the fact that the motor acts as a podded propulsor and will guide the kayaks body by pulling it at an angle, shown in figure 1.
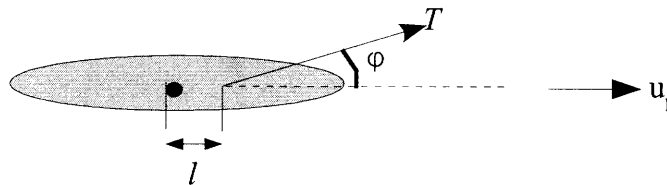

Figure 1. Illustration of thrust vector acting on kayak body.

To find the coefficient of drag, the knowledge of the terminal thrust was used. When the thrust force equaled the drag force on the kayak, the acceleration was zero and the two terms on the right side of equation 2 can be set equal to each other. The motor was at full power giving 40 pounds of thrust or 177.9 Newtons of thrust. From the GPS information, the maximum velocity was calculated to be 1.5 m/s. The length of the kayak is about 4 meters and the wetted area was taken to be about 5 meters squared. With these values and the value for the density of water, solving for C_D, yields a coefficient of drag of 0.03. This C_D corresponds to the thrust and drag forces experienced in testing the kayak in the Charles River. During these test a large pipe elbow was attached to the stern of the kayak to help with stability. A recent update to the body of the kayak are a pair of fins at the stern to help solve this stability problem. With these hydrodynamic fins instead of the bulky elbow, the C_D would be nearer to 0.02 for future runs.

The equation of motion in the yaw direction is also used to model the kayak dynamics. In this case, the sum of the torques around the center of the kayak is equal to the moment of inertia times the angular acceleration:

$$\sum \tau = J \ddot{\theta}_k \quad . \tag{3}$$

The torques, or moments, acting about the center of the kayak are due to the thrust from the motor and the drag as well. The motor is not located at the center of the kayak, so the force of the thrust acting at a distance causes a moment. In this model, the drag is approximately zero, leading to the following equation for the yaw direction:

$$J \ddot{\theta}_k = T \sin\varphi \, l \quad , \tag{4}$$

where J is the moment of inertia of the kayak in the yaw direction, T is the force of the thrust from the motor, φ is the angle of the motor, and l is the moment arm from the center of the kayak to the motor. These properties can also be seen in figure 1. The moment of inertia is about 25 kgm^2 and the moment arm is taken to be about 1 meter. The aerodynamic moments on the kayak have been neglected because it is only marginally stable, hence the aerodynamic center is near the mass center.

The last three equations, are formed to give the appropriate information needed to solve the differential equation for variables like x position, y position and the heading of the kayak. Using trigonometry,

$$\dot{x}_k = u_k \cos\theta_k \tag{5}$$

$$\dot{y}_k = u_k \sin\theta_k \quad , \tag{6}$$

where x dot is the component of the kayak velocity in the x direction, y dot is the component of the kayak velocity in the y direction, u_k is the kayak velocity and θ_k is the angle of the kayak.

In order to incorporate these equations into a program that will control the kayak's response to the data from the sensors, several models were created for the kinematics of the target vehicle. One popular path for AUVs is a lawnmower configuration in which the AUV scans an area in a series of linear sweeps. This motion was the basis for one of the kinematic models, as was, a simple turn, a straight line and a delayed start.

These kinematic models describe the x position and the y position of the target. These are the kind of data points that would be given by the acoustic sensors. Range and bearing can be defined with these points.

The range is the distance from the target to the kayak and the bearing is the angle from the target to the center line of the kayak. Range is given by

$$r = \sqrt{(x_v - x_k)^2 + (y_v - y_k)^2} \quad , \tag{7}$$

where x_v is the x position of the target vehicle, x_k is the x position of the kayak, y_v is the y position of the target vehicle, and y_k is the y position of the kayak. The bearing is given by

$$\psi = atan2\left(\frac{y_v - y_k}{x_v - x_k}\right) - \theta_k \quad , \tag{8}$$

where the first term is the angle in absolute coordinates and the second term is the angle of the kayak in those coordinates. With this equation, the bearing is the remaining angle that the kayak needs to turn to be pointing directly at the target.

The controller part of the program is where thrust and motor angle become functions of range and bearing. The thrust and motor angle are the current inputs to the computer on board the kayak. RoBoat successfully interpreted commands given a thrust and angle. The thrust control mechanism is purely proportional.

$$T = kr \tag{9}$$

Because of the omission of a drag component in the yaw direction, the control mechanism for the motor angle is both proportional and derivative.

$$\varphi = h_1 \psi - h_2 \dot{\theta}_k$$

The results below are parameterized with k, h_1, and h_2.

Results and Discussion

The simulation of the response of the kayak worked well under most conditions. The path of the target took on four major modes of operation, the lawnmower path, the simple turn, the delayed start and the straight line. These four paths are the most similar to the situations that the kayak will encounter in the field when tracking an AUV.
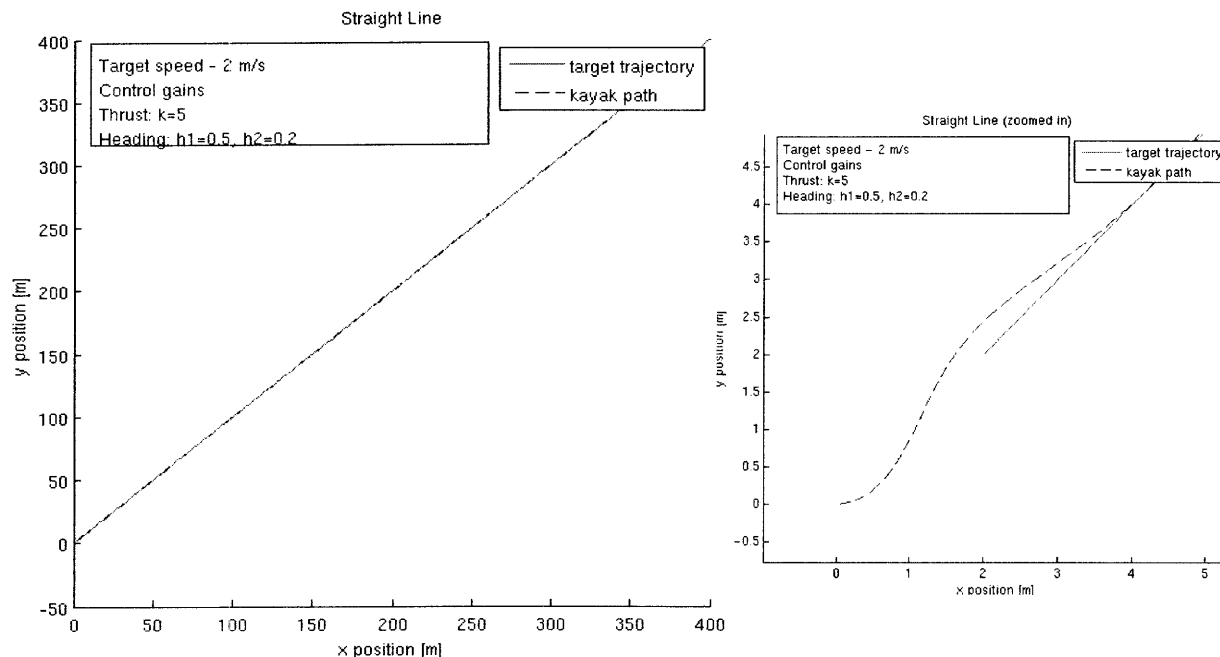
Straight Line path

Figure 2. Tracking a straight line target path. The kayak path is hard to discern because it is right on top of the target path unless the plot is zoomed in around the origin.

This plot is similar to many of the plots that will be examined for the four situations. This specific graph shows the positions of the target and the kayak in a two dimensional space. The time interval for this path is 200 seconds. All figures displaying position plots will start from the origin at (0,0) and proceed to be plotted in meters. The dashed line is always the path of the kayak, while the solid line always represents the path of the target. In the following discussion several variables were changed as the others were held constant to see what kind of differences in the kayak response would follow. The speed of the target and the kayak was varied, keeping a speed of 2 m/s as the control speed. The thrust control gain k was varied, with $k=5$ as the control. The heading control gains, h_1 and h_2 were also tested to find a change in response; the default setting for h_1 is 0.2 and for $h_2=0.5$. These three variables were varied in every case to understand their effects on the dynamic response of the kayak.

As shown in figure 2, often times with the straight line trials, the kayak path is difficult to discern from the target path because it lies right along it. However, at small scales and especially around the origin, the paths deviate as the kayak takes time to respond to the target movement.

What cannot be seen clearly on such a graph is the time delay, as in the distance lag, of the kayak with respect to the target. This delay in response can be seen in more clearly in the other situations.
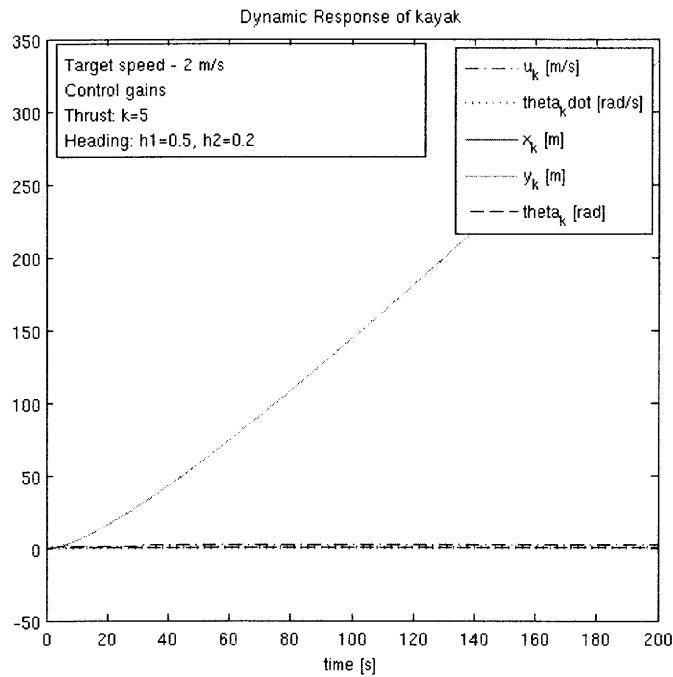
7

Figure 3. The dynamic response of the kayak vs. time with a straight line trajectory.

In figure 3, the five different relevant variables to the dynamics of the kayak are shown as a function of time. With five plots on one graph, it is not clear what is happening with each variable, but this is the basic shape to all graphs of this sort for all four situations. Many times this graph will only be shown when it provides interesting information, but otherwise these graphs can be found in the appendix.
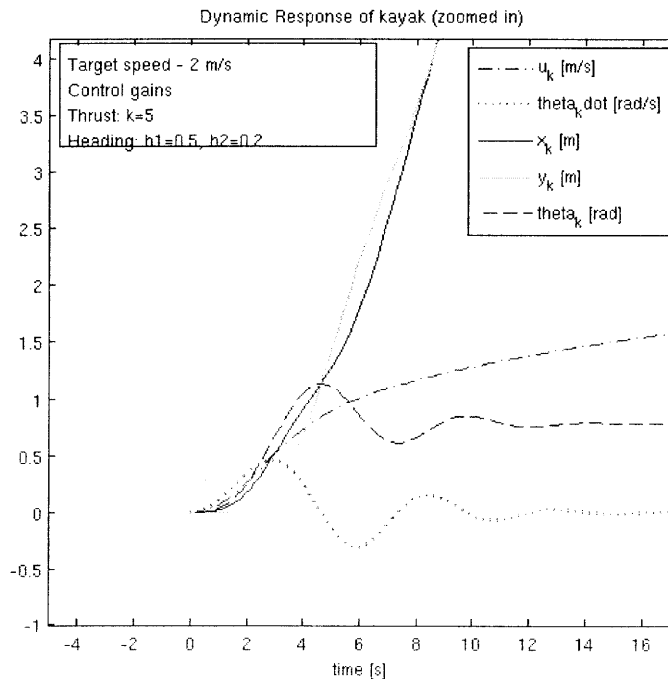

Figure 4. Zoomed in plot of figure 3 with clearly differentiated five curves.

Another typical sample for a dynamic response graph is shown above in figure 4. From this figure, it can be noted that x and y continuously increase, u_k asymptotically approaches 2, $\dot{\theta}_k$ stabilizes at 0, and θ_k reaches .75 radians or about 45 degrees. These results are positive because so long as the target is traveling away from the origin in the positive x, y quadrant, the x and y positions of the kayak should also increase. The velocity for the kayak is also set at the velocity of the target, so that it should approach 2. Also the angle of the kayak should be 45 degrees for a linear graph with a slope of 1, and the $\dot{\theta}_k$ or angular velocity should settle towards zero as the kayak homes in on the target.

The first quantity to be varied was the speed at which both the target vehicle and the tracking kayak are running. In the control simulation the speed is 2 m/s; in the next two situations the speeds are 1m/s and 5 m/s.
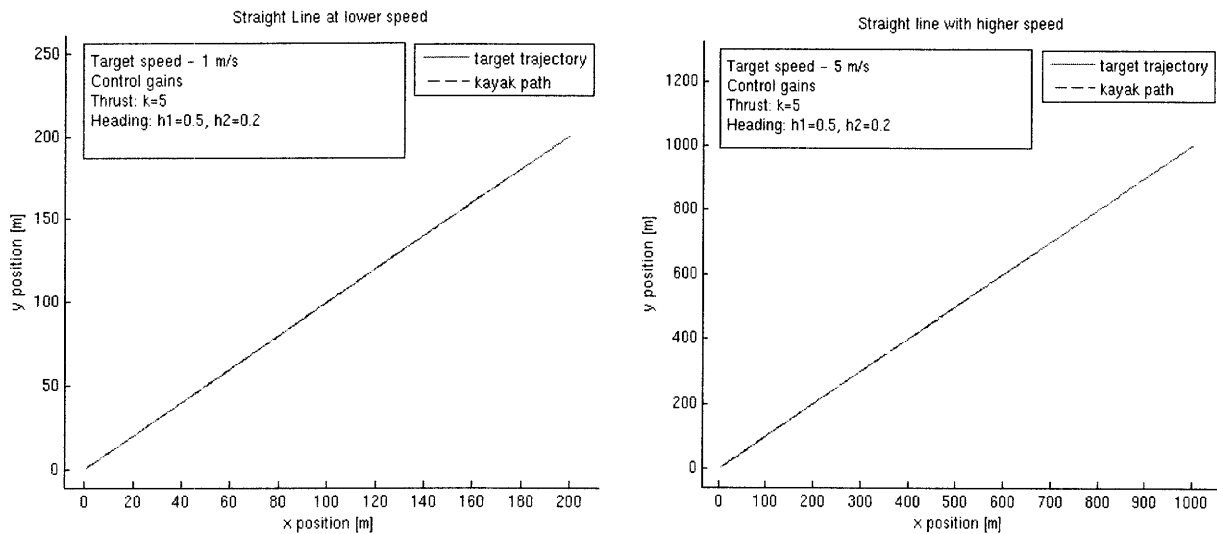

Figure 5. The paths of the target and the kayak with a straight target trajectory at two speeds.

Both graphs for both speeds are very similar to the control setting of 2 m/s. For a speed on 1 m/s, the kayak has the same response near the origin in that it wavers slightly before aligning itself directly with the target path. However for the 5 m/s case, the kayak does not waver nearly as much and follows the target path extremely well even from the beginning. The major drawback for a faster velocity and a seemingly more sensitive kayak response, is that in the end, at 200 seconds, the kayak lags the target in the x and y directions by 300 meters, while at the lower speed the lag is only 20 meters. The lag is more than ten times greater, while the increase in speed is only five times greater. Overall, with 300 meters difference in the x and y directions, the total distance of lag is about 424 meters; this is too far a distance to be considered effective tracking of an expensive AUV. Thus, at higher speeds this model should not be used to track an AUV, but at slower speeds the lag is acceptable and even though kayak wavers initially, it is not more than one meter, and then immediately corrects the errors to follow the targets path exactly.
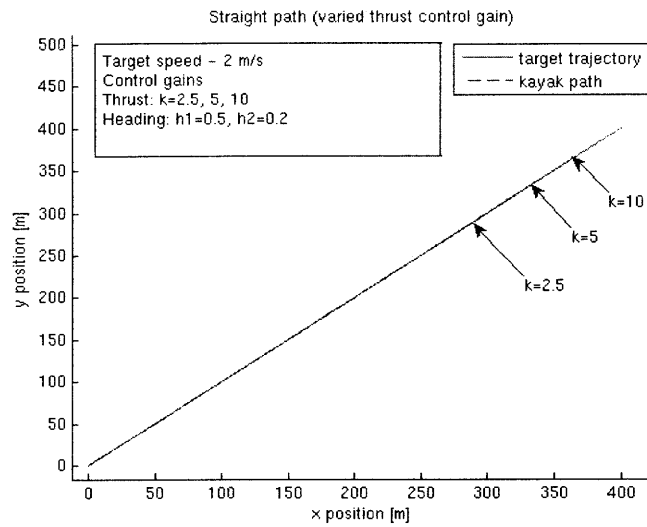
The next quantity varied was the thrust control gain, k.

Figure 6. Straight line paths of target and kayak as thrust control gain is increased.

When varying the thrust control gain, the major difference is the change in the trailing distance. Near the origin, the kayak response remains the same in that it wavers slightly before aligning itself with the target path, as shown in figure 2. While the beginning of the three simulations are similar and each kayak path also lines up right on the target pas as well, the end point is very different. At 200 seconds, the kayak path with the greatest thrust control gain has traveled the furthest. There is a non-linear relation ship between the values of the thrust control gain and the trailing distance. As each simulation doubles the previous control gain, the distance does not seem to be cut in half or even stay at the same difference. Because of this relationship, the following plot was made to better explain the effects of thrust control gain on trailing distance.
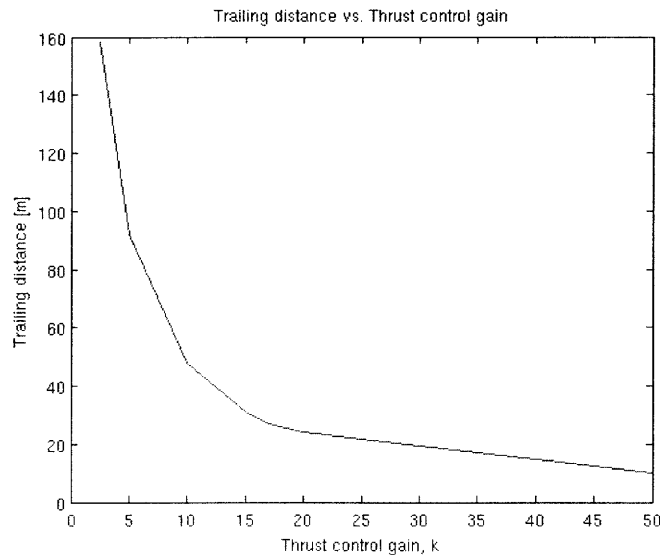

Figure 7. A plot of the relationship between the thrust control gain and the trailing distance.

If the thrust control gain were zero, then the kayak would not move an the trailing distance would approach infinity; also as the thrust control approaches infinity, the trailing distance would approach zero. This plot shows that the trailing distance exponentially decays as a function of the thrust control gain. The speed of the kayak for this graph was 2 m/s, but if the speed has been 1m/s the plot would look similar and lie below the line in figure 7.
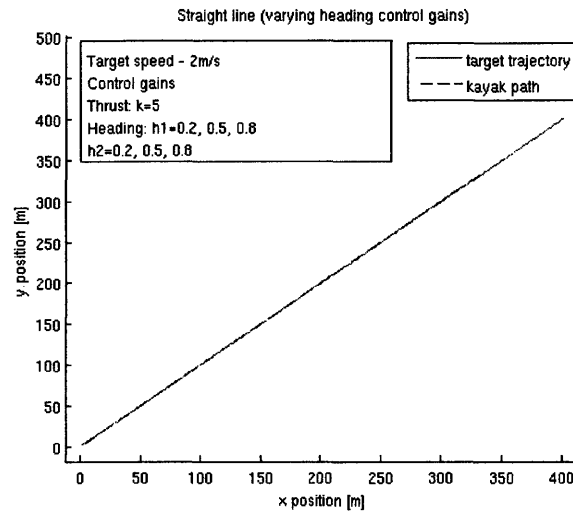
10

Figure 8. Straight line target trajectory with kayak response paths as the heading controls are varied.

Figure 8 is a typical plot of the target path and kayak paths as the heading control gains are varied. The heading variable changes the accuracy of the way the kayak tracks the target. As h2 was kept at 0.2, h1 was varied from 0.2, to 0.5 to 0.8; then as h1 was kept at 0.5, h2 was varied from 0.2, to 0.5 to 0.8. With these situations, the plot has 5 different kayak paths. This same process with these same values was repeated for the other situations as well. However, these are not quite visible in figure 8 because every path taken at these chosen gains is not noticeably different from the other paths. The greatest difference in the heading control effect on the kayak path, is again near the origin, but even at that location, the paths do not vary more than 1 meter. Considering that the kayak itself is about 2.5 meters, this variation is negligible. For the next situation, this typical large view of the effect of heading will be omitted and only a zoomed in plot will appear. The next situation is very similar to a simple straight line target trajectory.

Delayed Start Situation

For the delayed start situation, the target again follows a linear path with a slope of 1, but first does not move from the origin for 30 seconds. Because it has many similarities to the previous example, this section will highlight the major differences.
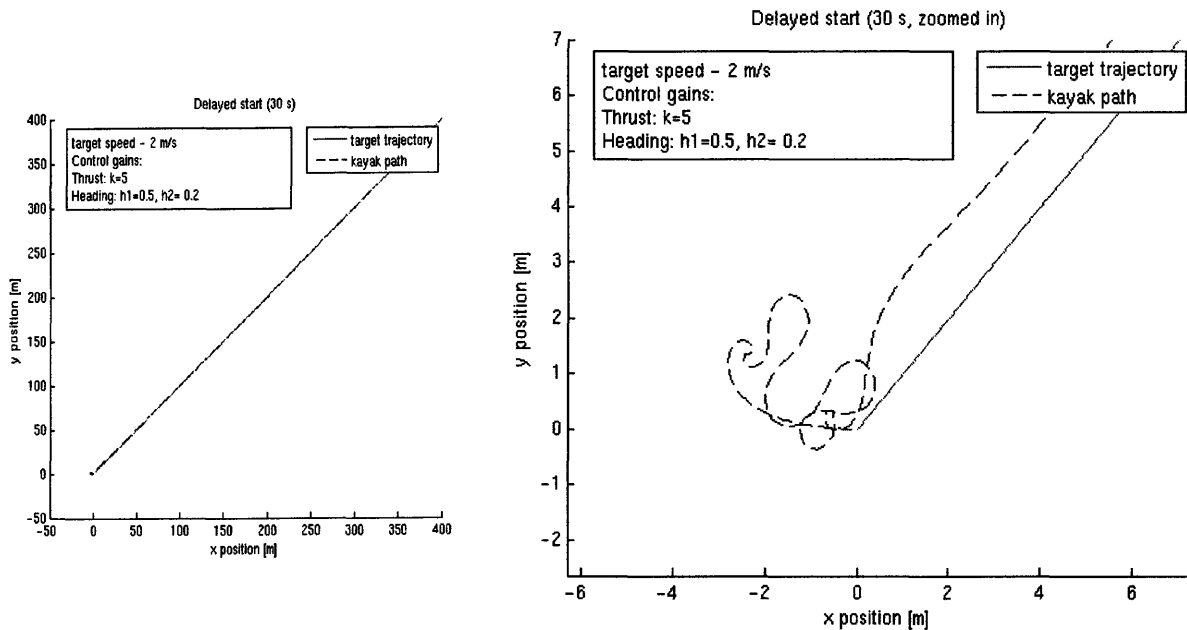
Figure 9. A similar plot as with the straight line path, but very different near the origin because of the delayed start. The right plot is a zoom in of the left plot around the origin.

While from the initial graph of the positions appears the same as for the straight line case, upon close inspection of the plot near the origin, a great difference appears as seen in figure 9. The straight line path had a slight waver near the origin, whereas the delayed start causes havoc for the kayak. The kayak response is not stimulated by any signals, so the kayak moves in an erratic manner. After the 30 s time period, the signal comes in and the kayak is able to track successfully the the remainder of the time. This response is better seen on the plot of the kayak's dynamics as shown in figure 10.
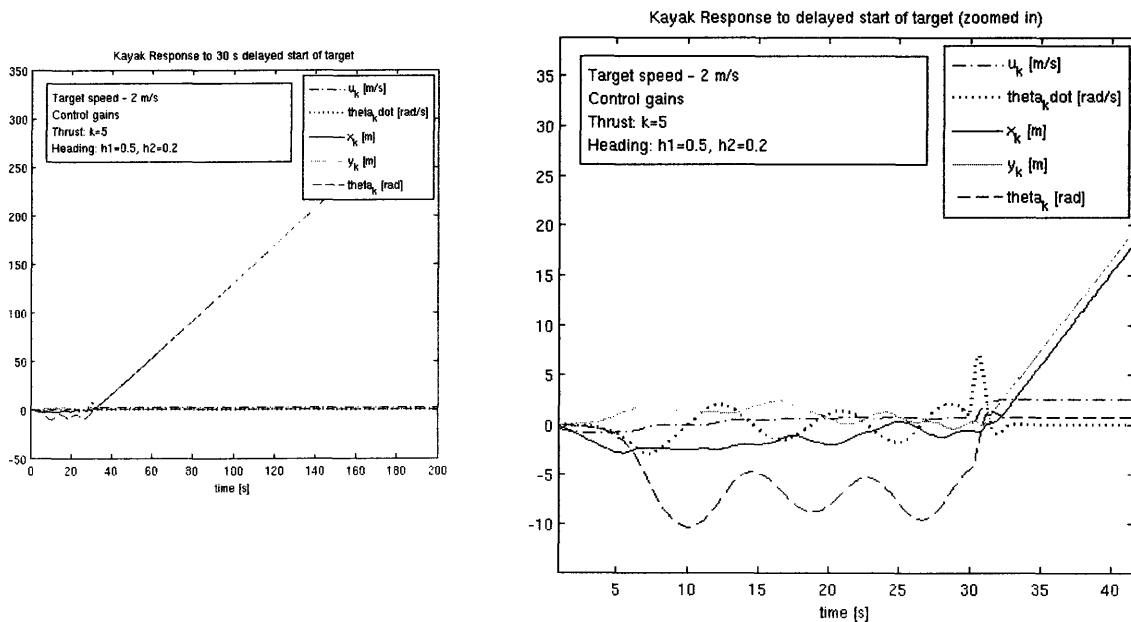

Figure 10. Dynamic response of kayak to a 30 second delay in the movement of the target with right plot as a zoom in of the first 30 seconds of the left plot.

12

The general shape of the dynamic response is similar to the straight line path response, but looking at just the first 30 seconds, the dynamics are clearly different. The angle of the boat varies greatly at first, but then immediately jumps to a steady state at 30 seconds. The velocity of the boat is relatively small until it reads in a signal as well. The x and y position of the kayak also stay within 5 meters of the origin. This is good because it shows that the boat will calmly meander in the same area as opposed to quickly leaving the site of the last known signal. Even though the kayak experiences confusion, everything acts accordingly and the kayak is able to respond normally when a signal is given. The kayak takes 1 second to start reading a difference in range and begin to correct for this.
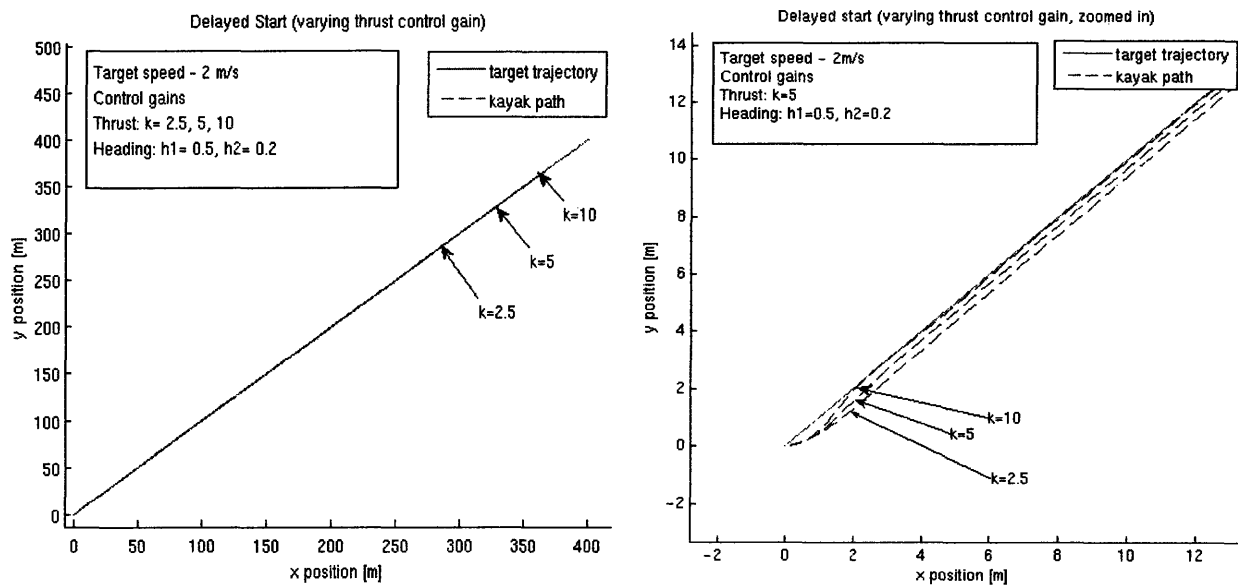

Figure 11. A closer look at the origin with a delayed target start, varying the thrust control gain.

With these plots, in figure 11, we can see that the thrust control gain makes little difference in the accuracy with which the kayak tracks the target, but makes a big difference in the trailing distance. The greatest distance difference in tracking is less than 1 meter and can be seen at the beginning of the paths near the origin (second plot in figure 11). Again the same relationship can be seen between the thrust control gain and the trailing distance as described for the straight line path. In real application, the kayak may not get a signal for some time if the acoustic setting were insufficient to read good data points when the AUV is directly below the kayak.
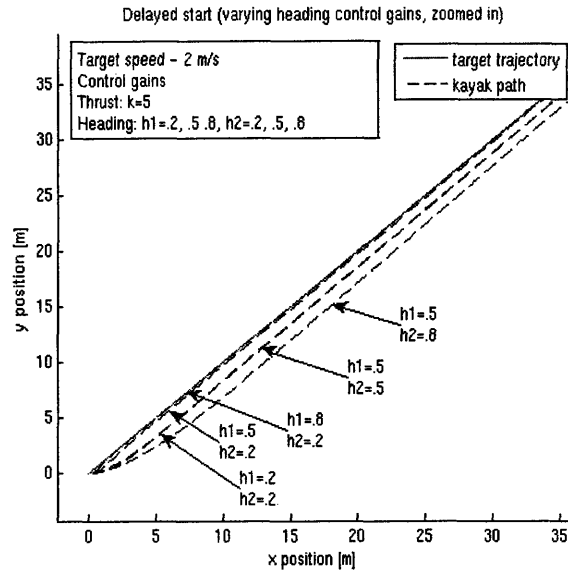
Figure 12. Target and kayak paths with a delayed start and varied thrust control gains.

The delayed start heading control variation plot is similar to that of figure 8, when the target traveled in a straight line. The differences lie in the response near the origin. In the straight line situation the kayak waver a little before following directly along the path of the target and the amount and shape of the waver changed with the heading control gain changes, but was less than 1 meter of difference in each case. For the delayed start, the differences near the origin due to heading control, are minimal but slightly more pronounced as the difference from one path to another is now nearer to 2 meters. Although the lines in figure 12 look parallel, the kayak will asymptotically approach the line of the vehicle for each case.

Simple Turn

This simple turn is a recreation of a random turn that could occur in the field. Because the lawnmower path consists of ideally right angle turns, and will be examined in the next section, this turn was modeled to be at an angel much sharper than a right angle. The AUV starts at (0,0) and proceeds to make a 120 degree left turn.
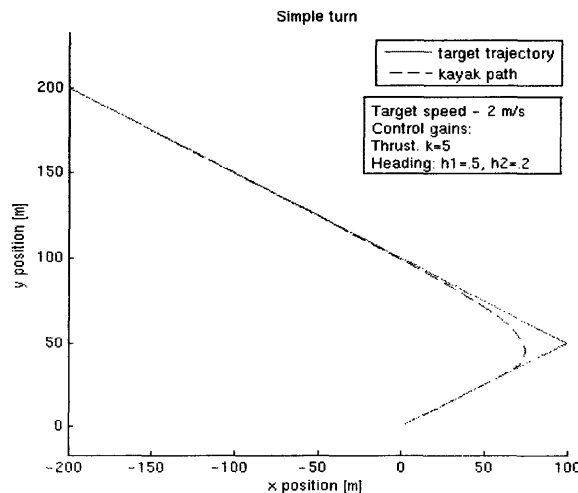

Figure 13. A simple turn: the kayak path (dashed line) and an idealized target turn (solid line).

The preceding figure (figure 13) represents the control model in which this is taken as the normal and the quantities are varied from this setting.
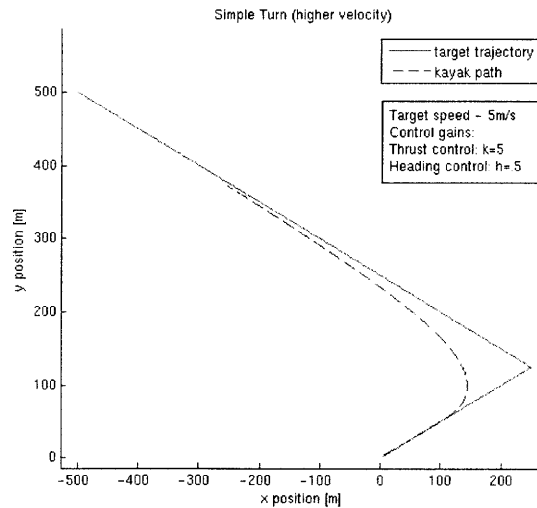

Figure 14. The same turn but with a speed of 5m/s as opposed to 2m/s.

While both of these figures have the same form, at higher speeds the kayak response is trails the target by a greater amount. At 2 m/s the largest difference in distance between the two paths is about 30 meters, while at 5 m/s this distance grows to about 75 meters. While this is nearly proportional, the graphs also show that the response at 5 m/s is not as quick to align itself with the target as at 2 m/s. In this 200 second period of time, the kayak path does not become blended with the target path in the second leg. Looking at figure 13, the dashed line becomes so aligned with the solid line at the end of the second leg of the path, that it is no longer distinct. This feature does not appear in figure 14. Another interesting observation is that the kayak responds nearly halfway through the first leg of the path a the higher speed. While the kayak is able to respond more quickly at a higher speed, it is not able to track a target moving at a higher speed with as much precision as when they are both at lower speeds.

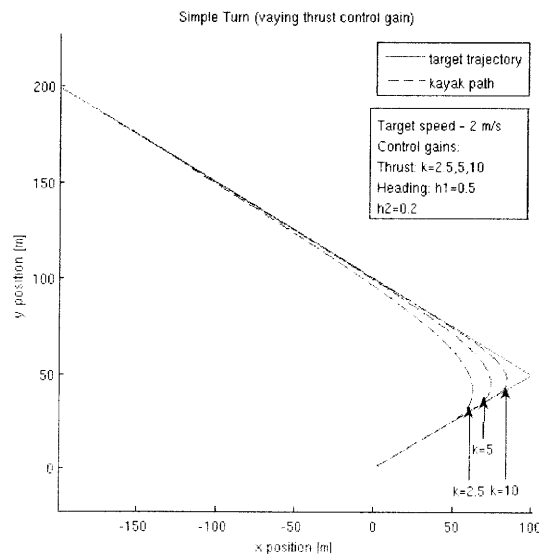For the simple turn, varying the thrust control gain yields the following plots.

Figure 15. The three paths of the kayak with different thrust control gains, as labeled in the plot.

This figure demonstrates that with an increase in the thrust control gain, the kayak can more closely follow the path of the target. Because the kayak speed is specified at 2 m/s, the increase in thrust, as you increase the gain, does not mean that the kayak goes faster, rather it indicates that the kayak can adapt more quickly to the changes in signals that it is receiving. At the end of 200 seconds, the path with the largest thrust control gain comes the closes to reaching the final point of the target vehicle.
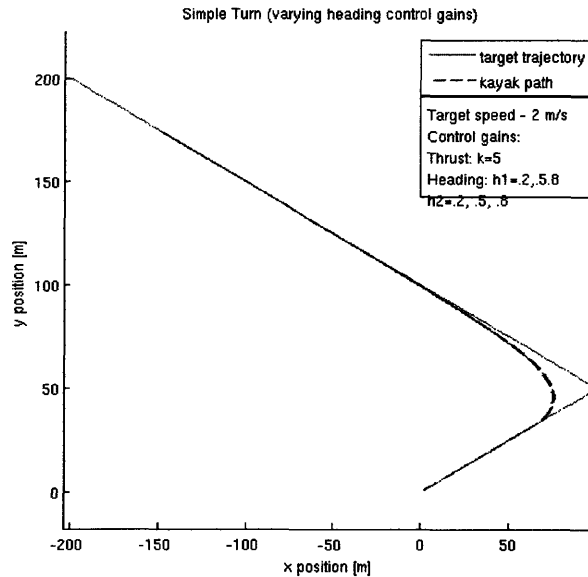

Figure 16. The various combinations of heading control gains plotted along with the target trajectory. While there are 5 kayak paths plotted, they appear as one because the are so similar.

In running several paths with different heading controls, they all appear as one on the graph. They are so similar and the impact of changing the heading control gain is so small that it is not noticeable on this scale of motion.

Lawnmower Path

In this path, the target goes in one direction for a long time, takes a ninety degree turn, the quickly after takes another ninety degree turn to head back in the direction that it came. It continues this process until it has covered a large surface area in this pattern.
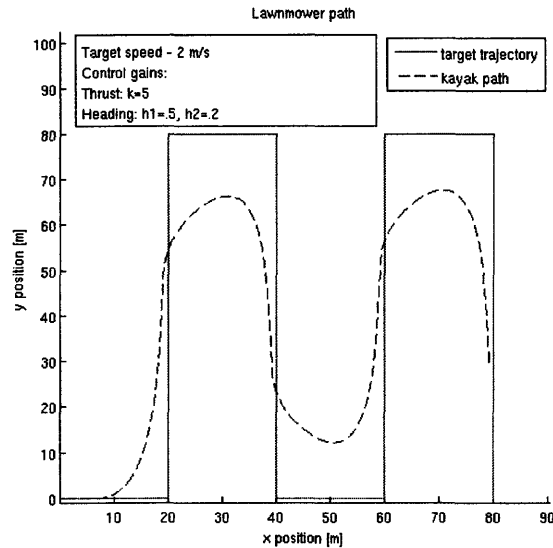

Figure 17. The lawnmower situation with target and kayak paths.

Figure 17 is a small sample of the type of pattern that would be repeated continuously by an AUV on a research mission. In this simulation the kayak model struggled the most to follow the target directly. As seen in figure 17, the kayak path never matched the target path, but was still following accurately. The three turns that occur as the kayak is turning are very symmetric, showing that the response of the kayak is reproducible and stable. The first variable that was changed was the speed of the vehicles.
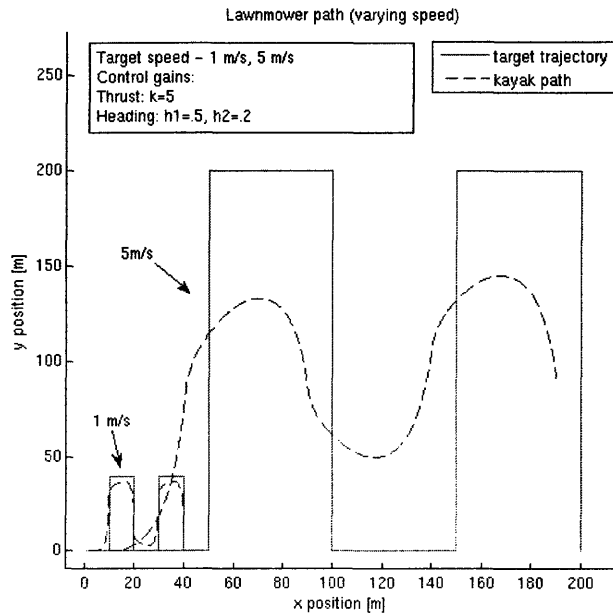

Figure 18. Lawnmower pattern with two runs overlaid at two speeds; both start from (0,0).

Figure 18 again shows that with this model, at faster speeds the kayak will react in an appropriate time scale, but will nonetheless be unable to align itself with the path of the kayak. At slower speeds the kayak is exactly in line with the target for a period of time before the target turns. Also the difference in distance between kayak path and target path at 1 m/s is less than 10 meters, while at 5m/s it is around 70 meters.
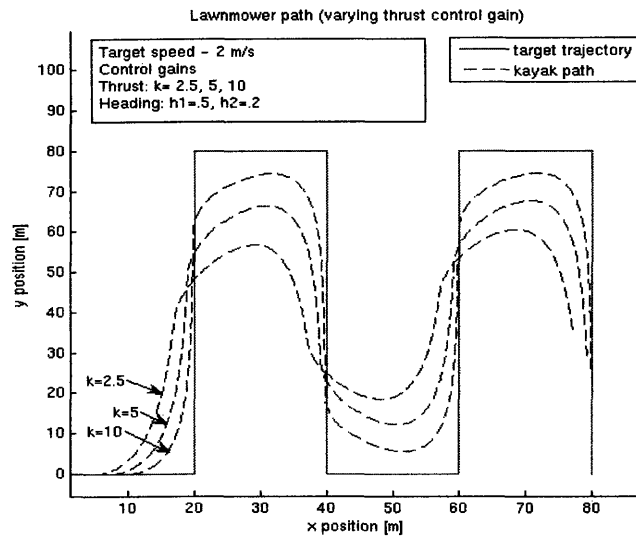

Figure 19. Lawnmower pattern with three thrust control gains.

Again, figure , shows that the thrust control gain has a large impact on the response of the kayak. The larger the gain the closer the kayak becomes to aligning itself with its target. Also at the end of the paths of the kayak, the differences in the end point show how much close the path with a high gain gets to the endpoint of the target. The k=2.5 line is lagging the k=10 line by about 10 meters at the end.

When varying the heading control gains, a similar graph appears as in figure 16 with the simple turn. All five plots of the kayaks path are so close that they seem right on top of each other. One last quantity that can be varied is the distance between the turns or the width of each scan.
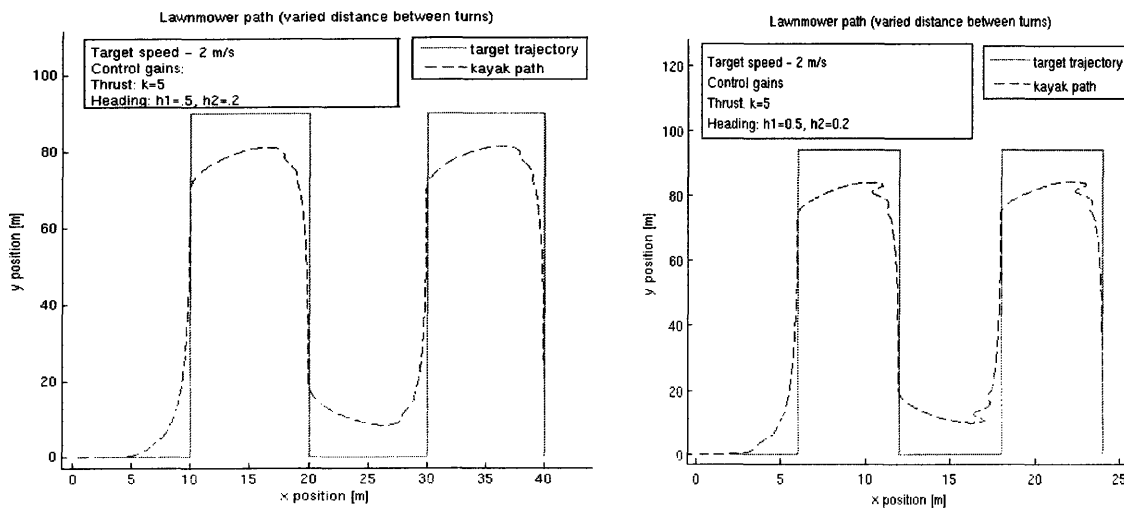

Figure 20. The lawnmower path with smaller distances between turns in the x direction.

The original distance between each vertical path was 20 meters; figure 20 shows two

18

different simulations, one with a 10 meter difference and the other with a 6 meter difference. At a 10 meter difference, the kayak begins to show an interesting and less smooth response the the sharp turns. At a 6 meter difference, it is clear that the kayak response is quick and initially overestimates the turn that it will be making. The dynamic model response shows oscillations in the theta value and in the x value corresponding to this quick adjustment by the kayak.
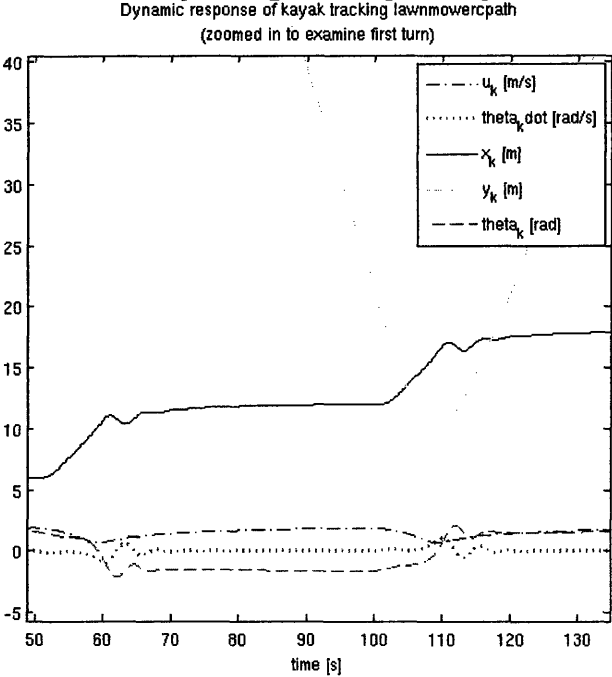

Figure 21. They dynamic response of the kayak when the distance between paths in the lawnmower trajectory becomes small.

Figure 21 illustrates the response of the kayak as it undergoes the first full turn around, between 5 and 12 meters for the 6 meter difference (the right plot of figure 20). While the kayak path in figure 20 shows some overshoot, the heading of the boat, θ_k, reaches a steady state in about 10 seconds. Looking at both figures 20 and 21, we can see that 30-40 seconds past the first overshoot (around 90 s), the kayak is already completely in line with the target trajectory (around x=12, y=40). As we make the distance between back and forth paths smaller and smaller, eventually the target can reach zero and theoretically make a 180 degree turn. The following paragraphs explore such an extreme case.
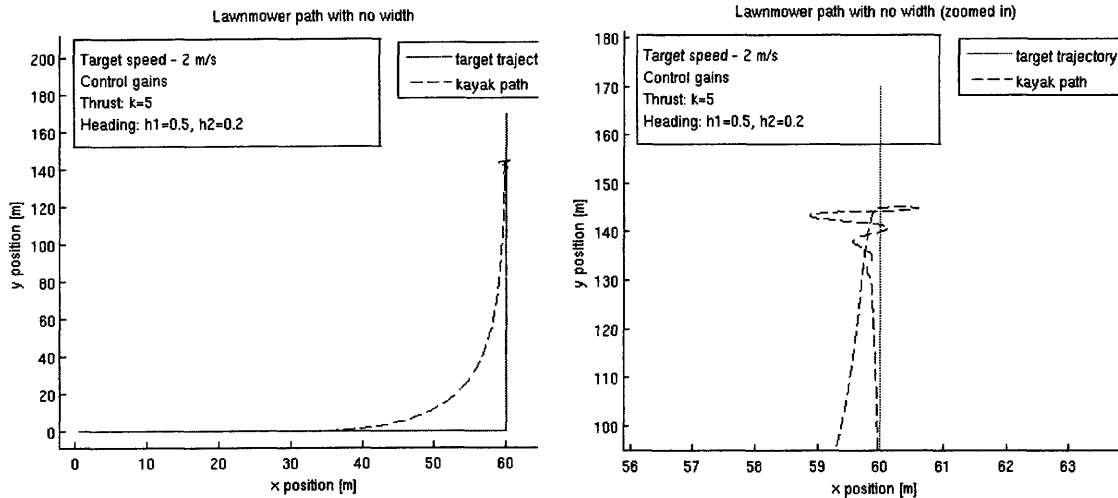
Figure 22. The response of the kayak path along with the target path as the target makes a left turn, then a 180 degree turn around. The right plot is a zoom in of the point at which the kayak turns around, 180 degrees.

In these graphs, the kayak path is nearly in line with the target path when the target makes the 180 degree turn. As the target does this, the kayak responds immediately by turning more than 180 degrees. As it does this it is constantly readjusting until the oscillations in the heading have settled and the kayak is pointed directly at the target again. These damped oscillations are shown in the left plot of figure 22. At a higher thrust gain the only difference is that the kayak path actually aligns itself with the target path as they travel up in the y direction. The kayak is then traveling in a straight line when the target turns around; the response and path that the kayak follows when attempting to follow the 180 degree turn is exactly the same as the figures above.
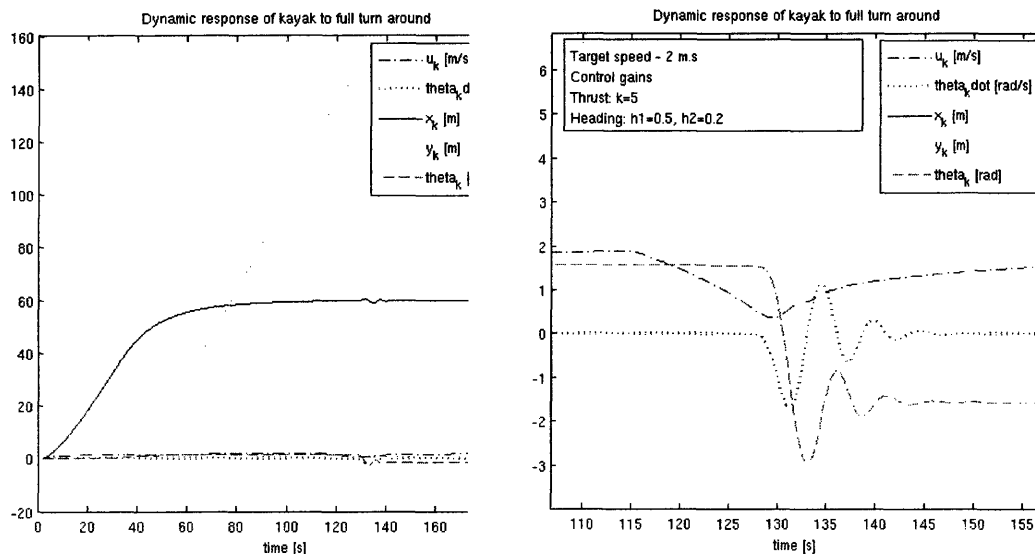

Figure 23. The response of the kayak's dynamic quantities as a function of time in the case where the target does a 180 degree turn. The right plot is a zoom in at the time of the turn.

The target makes its turn at 115 seconds, but because the kayak is trailing, the heading does not change immediately. The first quality to change is the kayak velocity which does seem to immediately slow down at 115 seconds. Both the heading and the rate of change of the heading (θ_k

and $\dot\theta_k$) reach a steady state after less than 25 seconds. Before a time of 115 seconds, the heading is about 1.6 radians which corresponds to about 90 degrees, and after the turn, the heading settles at about -1.6 radians which corresponds to about -90 degrees. This shows that within 25 seconds the kayak goes through a complete 180 degree turn and the heading steadies to be directly tracking the target.

To eliminate the overshoot seen by the kayak in response to a 180 degree turn or in the case of the lawnmower path with very little distance between sweeps, lower control gains should be used.

In trying different thrust control gains, I also tried a slightly different equation that would lead to the kayak attempting to keep a set distance between itself and the target. This desired range would be kept constant by the thrust of the kayak; however when testing this equation with the simulation, it made little to no difference in any of the four situations. The appropriate dynamic response and the way that the kayak path follows the target path show that this model for the kayak would work well.

Conclusion

In studying these four cases, the conclusions are that an increase in speed of both the target and the kayak will lead to a greater trailing distance but a quicker relative response rate. Increasing the thrust control gain will lead to a greater match in the target trajectory and the kayak path, and will decrease the trailing distance. Changing the heading control gains yields negligible differences in the response and the path of the kayak. For the lawnmower case, as the distance between back and forth paths became smaller the kayak response tended to overshoot the target path, then settle to a steady tracking within a minute.

Overall, this simple controller degrades in predictable ways. The trailing distance varies with the proportional thrust gain but in a manner that is also proportional to the square of the velocity. This was expected because of the relationship of the forces acting on the kayak as shown in equation 2. Also with quick turns from the vehicle, the kayak did overshoot its target path. However, there were no catastrophic failures. In all the cases encountered above, the kayak response was reasonable and the kayak was able to successfully track the target.

Possible improvements include a controller that is able to keep a constant range between the kayak and the target. This mode of operation would be useful for the collection of good acoustic data points. There is an optimum range for any acoustic sensors and tracking configuration to keep in order to get the clearest data. Another tracking scheme can also include the kayak tracking a target from an angle, as in not directly following the target. This would be useful if the AUV needed to be near a wall; the kayak should optimally not be driving near a wall where it can experience damage.