

Remote Manipulation of Cranes via the Internet

John Huey¹, Harald Bergur Haraldsson²,
William Singhose¹, Jason Lawrence¹, Jacques Fortier¹,
Sebastien Wolff¹, Sandro Kenji Sasaki², Eyri Watari²

¹ Dept. of Mechanical Engineering, Georgia Institute of Technology
Atlanta, GA, USA – e-mail: singhose@gatech.edu

² Graduate School of Science and Engineering, Tokyo Institute of Technology
Ookayama, Tokyo, JAPAN

Abstract

This paper analyzes the performance of crane operators when they are aided by an input shaping controller. The research compares an operator's ability to maneuver a crane through an obstacle course when the crane is operated locally to when it is operated telerobotically through the internet. This paper also studies the effect that course difficulty has on operator performance. Course difficulty is characterized by the number of turns required to complete an obstacle course and by a normalized measure of the path width between obstacles. The operation of both bridge and tower cranes is investigated.

Introduction

Cranes are an indispensable part of the infrastructure that supports oil drilling and exploration, mining, manufacturing, shipping and construction of all kinds. However, crane payloads often experience detrimental oscillations that degrade throughput and safety. Also, cranes are sometimes used to maneuver materials within hazardous environments that are unsafe for humans. In these cases, the only viable solution is to remotely control the crane from a safe location. Unfortunately, the remote operation of a crane presents several challenges, such as the addition of time delays within the communication loop between the human operator and the crane.

The goals of this study are twofold. The first goal is to compare local and remote operation. The second goal is to observe the effect of task difficulty and complexity on the performance of a crane operator. Volunteer operators drove both a bridge crane [1] and a tower crane [2] through obstacle courses that were both local to and remote from the operator. Operator performance was analyzed using several different obstacle courses. Performance was measured by run time (i.e. how long it took the operator to maneuver the crane through an obstacle field) and the number of collisions the payload had with the obstacle field. Operators were also tested in conjunction with an oscillation control algorithm that runs in real time to limit the payload sway. The experimental results indicate that remote manipulation of a crane via the internet is very challenging. However, the difficulty of the task is greatly reduced when oscillation control is utilized.

The oscillation control utilized here is input shaping [3, 4, 5, 6, 7]. Input shaping works by convolving a standard reference command with a series of impulses specifically designed to eliminate unwanted vibratory modes. Figure 1 depicts this process by showing a step command convolved with a two-impulse shaper to produce a staircase command that results in zero vibration.

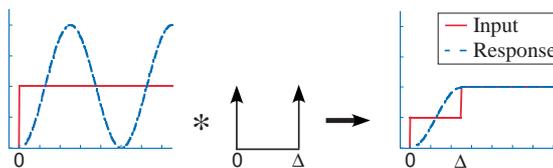


Figure 1. Input Shaping Process.

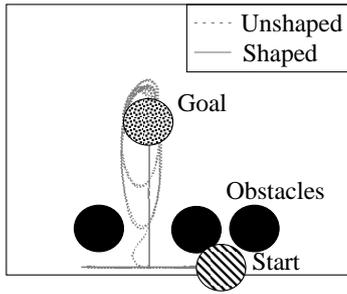


Figure 2. BC - Course #1.

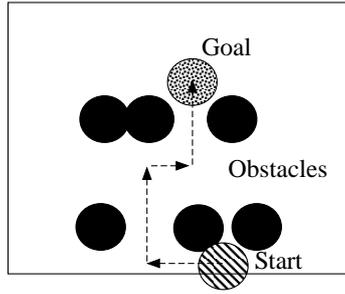


Figure 3. BC - Course #3.

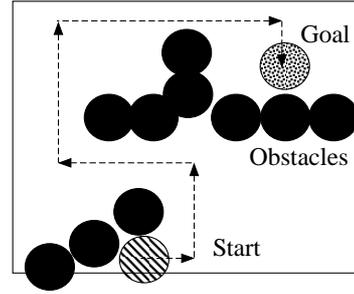


Figure 4. BC - Course #5.

Local vs. Remote Operation

Procedure - Bridge Crane in Atlanta, GA, USA

An overhead view of the bridge crane obstacle courses at Georgia Tech can be seen in Figures 2 through 4. For the “Local vs. Remote” study, only Course 3 was used. The other courses were used to study task difficulty. Three volunteers operated the crane remotely and locally. In each case, the crane was operated with and without input shaping enabled. Figure 2 depicts the oscillation reducing advantage gained with input shaping by plotting an unshaped and a shaped run. All tests were done twice, yielding a total of 24 runs. The operators were told that fast times and collision avoidance were equally important. The input shaper used was a single mode zero vibration (ZV) shaper [3, 4].

For local operation, the crane was controlled using a graphical user interface (GUI) on a computer directly connected to the crane. The GUI, similar to the one shown in Figure 5, allows the crane to be moved at full speed in four different directions (forward, reverse, left and right). It also provides a plot showing the layout of the course, the position of the crane trolley and the position of the payload. To reduce the difference between remote and local operation, the operators looked at this GUI plot while locally controlling the crane instead of looking at the actual obstacle course.

For remote operation, the same GUI was displayed on a computer in another room of the same building using a protocol called VNC. The time delay for remote operation was approximately one second.

Procedure - Tower Crane in Tokyo, Japan

Experiments conducted on a tower crane at Tokyo Tech utilized a setup similar to that described for the bridge crane at Georgia Tech. The GUI shown in Figures 5 and 6 was used for both local and remote operation. Figures 5 and 6 also depict the two obstacle courses used for testing on this tower crane. Note that the course in Figure 6 is more difficult than that in Figure 5. It has extra obstacles that require the payload to move through narrow passages. The comparison between local and remote operation was performed on the more difficult course. Several people with varying levels of expertise operated the crane both locally and/or remotely. The remote runs were performed both within Japan and from other countries such as the USA. The operators experienced various levels of delay depending on their remote location.

Results - Bridge Crane in Atlanta, GA

Figure 7 plots the average task completion time for Course 3. Remote operation obviously leads to increased run times, with an average increase of 24 seconds (75%) without input shaping and 13 seconds (60%) with input shaping. The use of input shaping leads to substantial time savings in both remote and local operation.

The main issue that caused longer run times for remote operation was the uncertainty created by the variable time delay. This made it difficult for the operators to

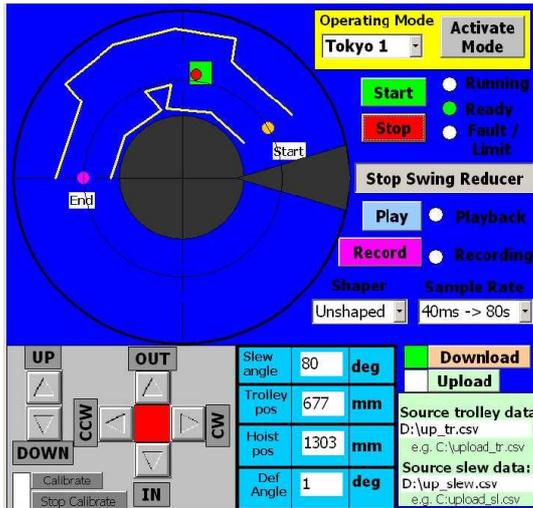


Figure 5. "Tokyo 1" Course.

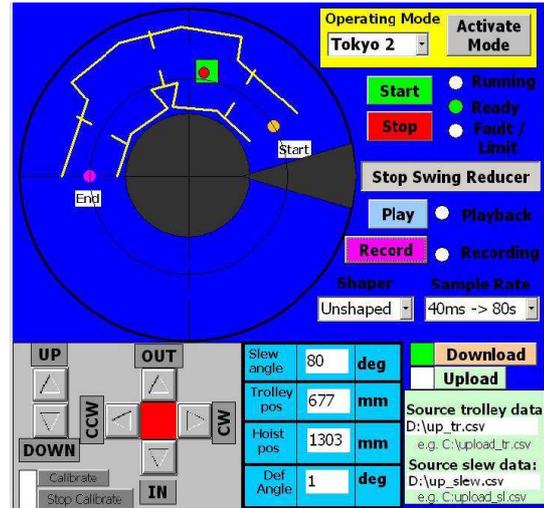


Figure 6. "Tokyo 2" Course.

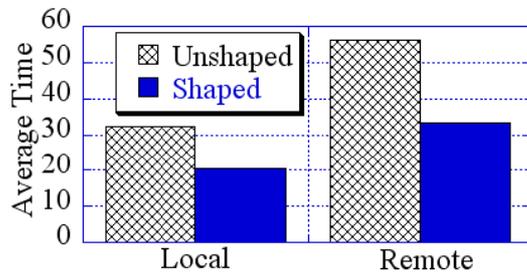


Figure 7. Bridge Crane Study - Run Times.

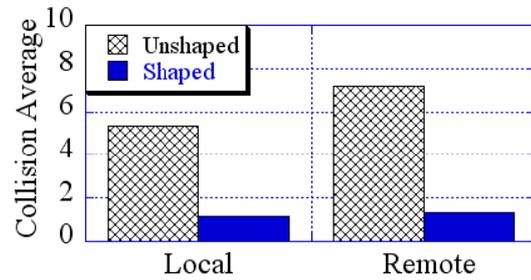


Figure 8. Bridge Crane Study - Collisions.

execute precise commands. In some cases, the operator needed to make five or six adjustments before getting the crane to the correct position. When operating locally, such adjustments could usually be made with a single command. Input shaping is not particularly effective at solving this problem, so it is expected that run time would degrade when moving from local to remote operation, even with input shaping enabled.

Figure 8 shows the average number of collisions that occurred during each test. The obvious result is that input shaping nearly eliminated collisions with obstacles. Without input shaping, remote operation increased the average number of collisions by 2.1 (40%), while it only increased the average by 0.1 (10%) with input shaping enabled.

The decrease in collision count when moving from remote to local operation without input shaping is explained by the ability of the operator to take corrective action more quickly. Most of the collisions were caused by payload oscillation. With local operation, the operator has faster feedback and can move the crane in such a way as to perform some form of manual oscillation cancellation. Because of the long and varying time delay, remote operation makes it nearly impossible to manually cancel oscillation.

The relatively small improvement in collision count when moving from remote to local operation with input shaping enabled has a similar explanation. Because the primary cause of collisions was payload oscillation, the ability of input shaping to nearly eliminate oscillation solved the collision problem in both the remote and local tests.

Results - Tower Crane in Tokyo, Japan

Figure 9 shows the run time values for the tower crane at Tokyo Tech. Remote operation increased the run time by approximately 15%, while input shaping lead to significant time savings. Figure 10 shows the average number of collisions. As seen in these results, the average number of collisions without input shaping slightly increases when the

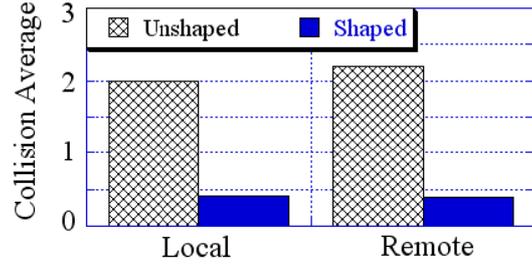
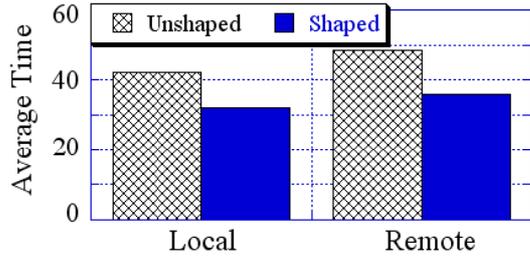


Figure 9. Tower Crane Study - Run Times. **Figure 10. Tower Crane Study - Collisions.**

crane is run remotely, but the same does not occur with input shaping. This supports the results obtained from the experiments conducted on the bridge crane in Atlanta, indicating that when input shaping is applied to remote operation the number of collisions is not significantly increased compared to local operation. Note that there is some uncertainty in the number of collisions. When the payload barely touches an obstacle, it is difficult to state definitively that a collision occurred. The number of collisions was determined by analyzing the recorded trajectory of the crane payload, as well as the X and Y velocity components, to detect the irregularities in the trajectory when the payload collided with physical obstacles. Only collisions that induced a noticeable change in velocity were counted.

Effect of Course Difficulty on Crane Operation

Procedure - Bridge Crane in Atlanta, GA, USA

The second part of this investigation sought to determine the effect of course difficulty on the operation of cranes. Using the three different obstacle courses shown in Figures 2 - 4, each operator performed two runs with input shaping disabled and two runs with it enabled. All of the runs were performed remotely, as described in the “Local vs. Remote” tests of the previous section.

The courses shown in Figures 2 - 4 are named after the number of turns required to complete the course. The arrows shown in Figures 3 and 4 (and the input shaped path shown in Figure 2) indicate the general routes the operators were expected to follow. Course difficulty is defined here as the number of turns an obstacle course requires the operator to perform.

Procedure - Tower Crane in Tokyo, Japan

The tower crane studies also compared operator performance as a function of course difficulty. However, these trials focused on local operation, whereas the bridge crane tests in Atlanta focused on remote operation. For the tower crane operation study, course difficulty was precisely defined. The difficulty level D was defined to be the ratio of the payload suspension length, h , and the width of the path between the obstacles, w . This gives a quantitative level of difficulty, based on how much a payload can swing without colliding with an obstacle:

$$D = \frac{h}{w} \quad (1)$$

A larger value of D indicates a more difficult course. The easiest level would be when the path width is equal to or larger than twice the payload suspension length. In this case, the payload could swing freely, since the path is wide enough for any swinging amplitude.

As the difficulty level D becomes larger, the payload’s swinging amplitude must be contained so as not to collide with obstacles. The level of difficulty can be increased until the width of path is equal to the payload diameter, $w_{payload}$. Therefore, the maximum difficulty level (for a given length, h) is $D_{max} = \frac{h}{w_{payload}}$.

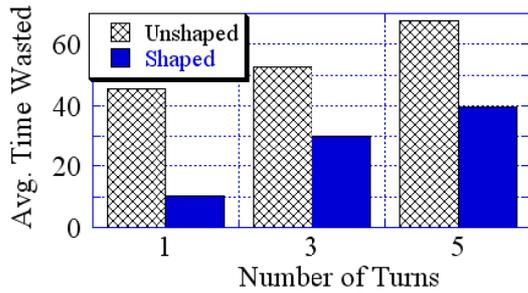


Figure 11. Bridge Crane - Time Wasted.

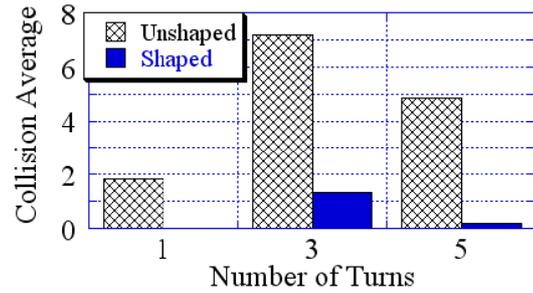


Figure 12. Bridge Crane - Collisions.

After defining difficulty, two rigid obstacle courses were constructed with the same length and the same number of turns. Only the width of the path was changed. These two courses were shown in Figures 5 and 6 and are named “Tokyo 1” and “Tokyo 2”. Simple examination of Figure 5 shows that the “Tokyo 1” course is easier than the “Tokyo 2” course. This conclusion is confirmed by the difficulty level values given here: $D = 3.7$ for “Tokyo 1” and $D = 8.7$ for “Tokyo 2”.

Results - Bridge Crane in Atlanta, GA, USA

As can be seen from Figures 2 - 4, the nominal path length from start to finish increases with course difficulty. This means that it should take longer to complete Course 5 than Course 1. Therefore, in an attempt to fairly compare run times for each course, the completion time was normalized by subtracting the optimal time to complete each individual course. The optimal time was calculated by first establishing a nominal path through each course, similar to the paths shown in Figures 2 - 4. The nominal paths were characterized by simple straight line motions roughly centered within the spacing between obstacles. The optimal time for each course was then determined by calculating the time required to traverse the nominal path at maximum velocity. The time wasted on a course was then obtained by subtracting the optimal time from the actual run time.

The average time wasted for each course is shown in Figure 11. The results clearly demonstrate that input shaping greatly improves performance. With or without shaping, it is clear that increasing the number of required turns increases the average time wasted. These results are expected, because before each turn the operator must ensure that the trolley is properly positioned and that the oscillation is low enough for the payload to fit through the next obstacle gap.

Figure 12 shows the average number of collisions that occurred. As one would expect, the easiest course had the fewest number of collisions, and input shaping substantially reduces collisions. However, the results for Course 5 seem counter-intuitive. For both operation modes, Course 3 resulted in more collisions than Course 5. The reason for this phenomenon is that the turns in Course 3 were tight, with many obstacles completely surrounding them and allowing little room for error. On the other hand, many of the turns in Course 5 were delimited by obstacles on one side, and a workspace limit on the other side. As a result, the payload was significantly less likely to collide with obstacles, as exceeding the workspace limits was not considered a collision.

Another possible contributing factor to the low collision rate on Course 5 is learning. Each of the three operators ran the courses in the same order: Course 3, Course 1, Course 5. Because Course 3 was run first, it was run with the most inexperienced operators. However, by the time Course 5 was run, each of the operators had already driven the crane at least eight times.

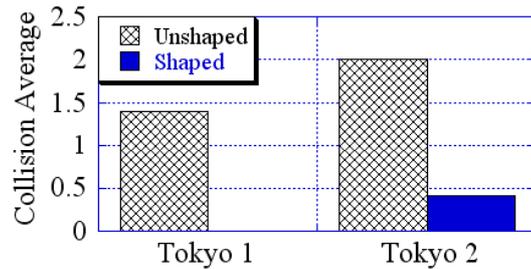
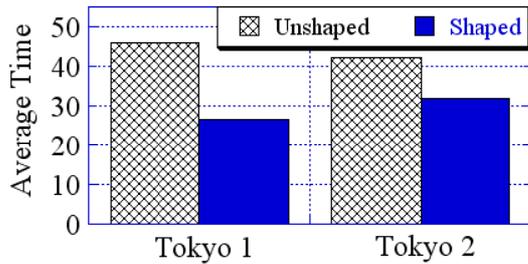


Figure 13. Tower Crane Study - Run Times. Figure 14. Tower Crane Study - Collisions.

Results - Tower Crane in Tokyo, Japan

Figure 13 shows the run time results for the tower crane tests. The results indicate that the unshaped run time of the difficult course is shorter than for the easy course. This is counterintuitive, but can be explained by learning, similar to the Atlanta results. Each operator began on the easy course, acquiring skills before proceeding to the more difficult course. However, the average number of collisions increases when the level of difficulty is increased, as shown in Figure 14. The most important and convincing result from this series of tests is that when input shaping is used, both collisions and completion time are significantly reduced for both courses.

Conclusions

The experiments reported here confirm the increased difficulty associated with remote operation of cranes. Increased and varying time delays led to longer task completion times and more collisions when the cranes were tele-operated. Course difficulty also generally increased move times and collisions for both local and remote operation. Fortunately, the addition of an oscillation-reducing controller (input shaping) allowed for substantially faster and safer manipulation, regardless of course difficulty or operating mode.

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