INPUT SHAPING CURRICULUM: INTEGRATING INTERACTIVE SIMULATIONS AND EXPERIMENTAL SETUPS

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***Abstract*-Input shaping has been shown to be a simple way of reducing vibration in gantry cranes. This is particularly important if the crane must operate in a cluttered workspace. A real-time MATLAB simulation of a gantry crane in a cluttered environment has been developed. It was used in an undergraduate controls course to teach both dynamics and input shaping. Data from these simulations show that students drove the crane through more efficient paths when input shaping was used. An input shaping controller has been implemented on a large gantry crane at the Georgia Institute of Technology. Use of this crane in the undergraduate curriculum is discussed.**

Index Terms: **Education, Dynamics, Controls, Crane Simulation**

I. INTRODUCTION

When a human operator attempts to maneuver payloads using an overhead gantry crane like the one sketched in Figure 1, the oscillations induced into the payload by the motion of the trolley can be significant. The crane oscillations make it difficult to manipulate the payload quickly and with good positioning accuracy. Furthermore, when the workspace is cluttered with obstacles, the oscillations can create significant safety issues, especially when the payload or obstacles are of a hazardous or fragile nature. This problem serves as an excellent case study for students of dynamics and controls.

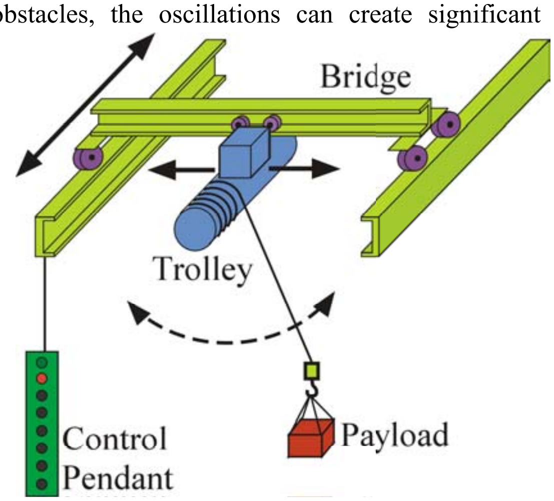

Figure 1: Sketch of a Gantry Crane.

A. Review of Input Shaping

Input shaping is a simple, effective strategy for reducing crane sway [1]. Input shaping is easier to derive and implement than time-optimal control schemes and does not require the feedback mechanisms of closed-loop and adaptive controllers. Input shaping is implemented in real time by convolving the command signal with an impulse sequence (an input shaper). This process is illustrated in Figure 2 with a step input and an input shaper containing two positive impulses.

B. Educational Benefits

This research was designed to supplement traditional homework and lecture material with interactive and real world examples of dynamic, flexible systems and the vibration control techniques used to safely and quickly move them [2]. A series of homework problems was created which slowly introduced the students to various details about the dynamics and control of gantry cranes. Towards the end of this series of homework problems, a gantry crane simulation with a graphical user interface was introduced. Students were able to safely experience crane dynamics and the benefits of input shaping by driving the crane in the simulation. In addition to the simulation showing the effects of input shaping, The Georgia Institute of Technology has a large gantry crane that has been equipped with an input shaping controller. With this system, the students will also be able to see and control a real crane, as well as experience first hand the vibration reducing capabilities of input shaping.

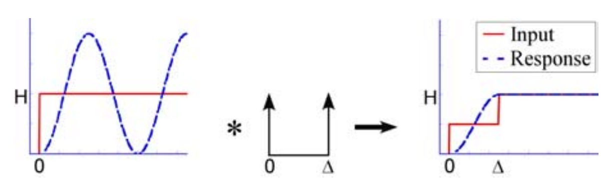

Figure 2: Input Shaping a Pulse Input.

Integrating technology into engineering education greatly enhances teaching efficacy. Past studies have shown that "visualization and simulation tools will allow students to move beyond a focus on calculation methods toward the development of engineering judgement through the rapid explanation of alternative solutions and problem formulation" [3]. This was exactly the intent of exposing the students to the interactive crane simulation and real gantry crane. Furthermore, utilization of internet technology (the crane simulation is available on the web) allows the students to perform the experiments at their convenience. This asynchronous learning environment fosters learning in a demanding academic schedule.

C. Research Benefits

In addition to helping students learn classroom material, the gantry crane simulation program was used to study the effect of input shaping on operator behavior. The students were allowed to control the simulated crane both with and without input shaping. The paths taken by each student were recorded by the program and analyzed for trends. The results show that the presence of input shaping increases the likelihood that an operator will take a more efficient route through obstacles as opposed to taking a long route around an obstacle field.

D. Summary of Paper

The next section of the paper briefly describes the homework problems that were used to introduce the crane dynamics and the input shaping process. Section III then discusses the crane simulation that was developed. Section IV presents data that was collected from students using the crane simulation. Section V describes the real gantry crane that is equipped with input shaping at the Georgia Institute of Technology. Conclusions are discussed in Section VI.

II. HOMEWORK PROBLEMS

A series of homework problems progressively increased the students' understanding of gantry crane dynamics and control. These problems were intended to introduce the students to the MATLAB software's capability to produce plots of the system response, to teach the students how to combine mechanical and electrical subsystems, and to demonstrate how input shaping cancels vibration.

The first problem required the students to derive the dynamic model of a planar gantry crane similar to the three-dimensional crane shown in Figure 1. Students then used MATLAB to plot the response of the crane to several inputs—step, pulse, and bang-bang functions.

For the second homework assignment, the students were required to add a motor to the planar gantry crane from the previous assignment. The result is that the motor delays the crane response. The students utilized MATLAB to plot the response of the new system to a bang-bang function.

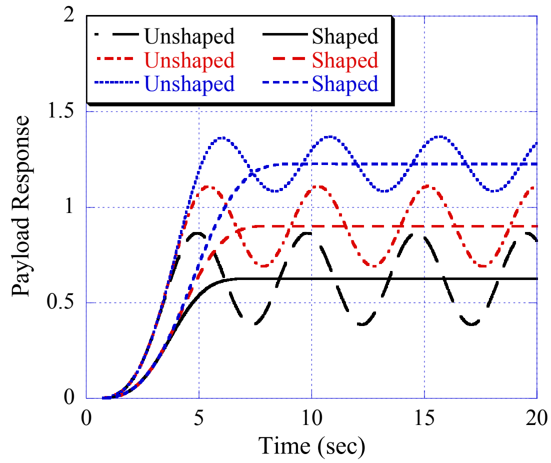

Figure 3: Response of Crane to Bang-Bang and Shaped Commands.

In the third homework problem, the students were required to analyze the response of the original planar crane model to two different inputs. These inputs were a bang-bang function and an input-shaped bang-bang function. The resulting payload response plots are shown in Figure 3. The figure shows shaped and unshaped responses for three move distances.

The students were asked to comment on the responses observed. Most recognized that the vibration had been "cancelled" in some way for the input shaped command. They speculated as to how this had occurred, noting that input timing would need to relate somehow to the system's natural frequency. Classroom instruction reinforced these concepts, showing the students how inputs to the system, timed appropriately according to the system's natural frequency and damping ratio, could cancel residual vibration.

III. CRANE SIMULATION

The students were given a MATLAB simulation of a gantry crane existing in a cluttered workspace. The operator's viewpoint is directly above the workspace, as shown in Figure 4. The workspace contains a starting zone, goal region, obstacles, and the crane trolley and payload. The crane's trolley was controlled by using the numeric keypad on a computer's keyboard.

The objective was to get from the starting zone to the goal region in the quickest and safest way possible. The level of safety pertaining to any particular path was determined from the number and severity of collisions between payload or trolley and the obstacles in the workspace.

Each student was also given a score based on their performance. The score consisted of the time to completion plus time penalties that were added for collisions. The time penalties were weighted by the severity of the collision with an obstacle. In this setup, a low score is desirable. At the end of each trial, the student's score was displayed to them, and they were allowed to either accept this score or try again.

Although scoring did not influence grades, giving the students a score ensured some level of effort from the students. In real life, a crane operator must be very careful to avoid collisions between the payload and obstacles. These could result in an injury or a damaged payload. On the other hand, a crane operator must work with a high level of speed and efficiency. Therefore, a real crane operator must make tough decisions about how fast to go and what paths to take in a cluttered work environment. In this computer simulation, there is no loss of a job or personal injury. Therefore, by scoring the students performances, and by penalizing their score for collisions, it was thought that natural competition would result in students rationally deciding on which path to take.

Each student was allowed to run the crane with and without input shaping. This allowed each student to see the benefits of a vibration control scheme like input shaping. In addition, the different path choices taken by students with and without input shaping revealed some important information about how this vibration control technique effects operator decisions. In particular, it showed that operators tend to be more aggressive and thus take more efficient routes when input shaping is available. An example of an unshaped control of the crane and a shaped control is shown in Figure 5.

In addition to the different control strategies available, each student was assigned a specific course within which to operate the crane. There were two courses of differing difficulty that were used in this simulation. The design of two courses with different difficulty levels allowed for a more thorough study of input shaping's impact on operator decisions. Half the class drove the crane through the "Easy" course shown in Figure 6, and the other half drove through the "Hard" course shown in Figure 7. The "Easy" course has fewer obstacles and simpler path possibilities than the "Hard" course. In the simulation, the students drove the crane throughout a course first without input shaping, then with input shaping enabled.

The path each student took during the simulations was recorded by the program. In order to quantify these paths, each student was categorized as having either taken a long path or a short path from start to finish. An example of long and short paths is shown in both Figure 6 and 7.

IV. RESULTS

The results gathered from the Fall 2002 undergraduate System Dynamics and Controls class containing 46 students indicate that the presence of input shaping greatly influenced the way in which the students drove the crane throughout the obstacle field. On the "Easy" course, with no vibration control enabled, 54% of the students chose to take a quick route from start to finish, while 46% took a long route. However, on this same course, when input shaping was enabled, 96% of the students took a quick route and only 4% of the students (1 student) took a long path. This is a 40% shift from the long, safe route to the quicker, more dangerous path.

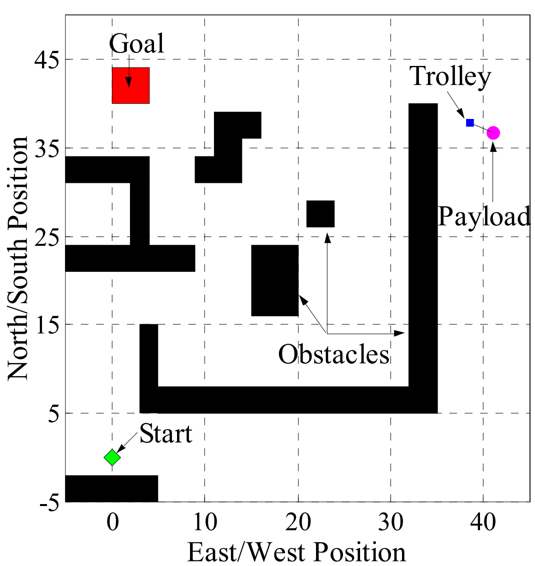

Figure 4: Overhead View of Crane Workspace.

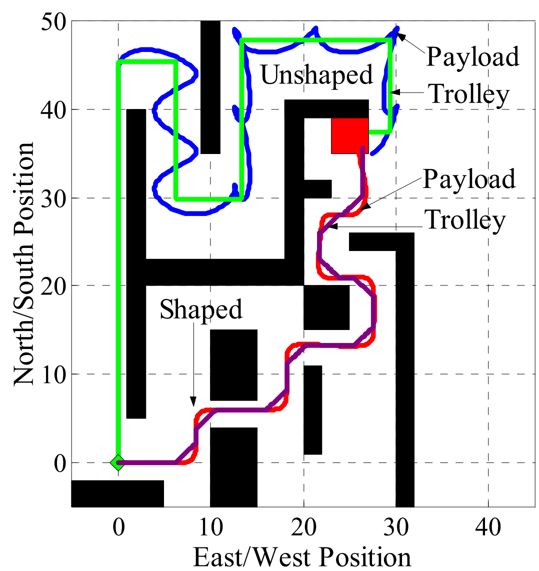

Figure 5: Path Examples.

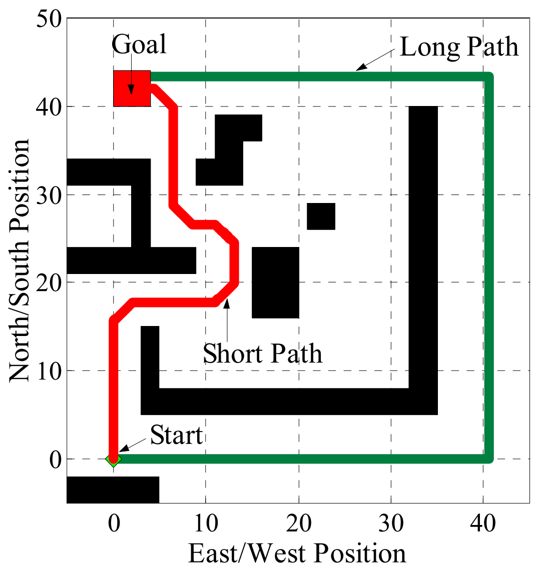

Figure 6: Easy Course.

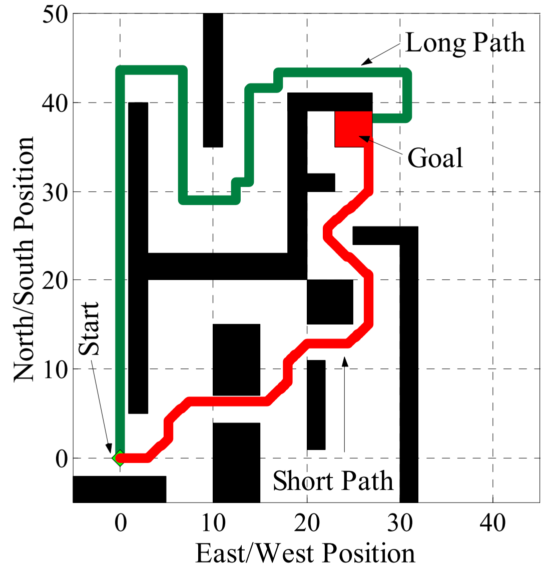

Figure 7: Hard Course.

On the "Hard" course, with no vibration control, only 24% of the students chose to go along the quick path, whereas 76% of the students chose the safe, long route. However, when input shaping was enabled on the "Hard" course, 65% of the students chose the fast route, while 35% chose the long path. Again, this is a 40% shift from the long path to the short, more dangerous route. From these results, it is clear that input shaping does have a significant effect on the way in which crane operators chose to move a payload.

Another interesting result came from a questionnaire given to the students about this assignment. The purpose of this questionnaire was to determine the students' opinion as to how interesting and effective this project was in teaching them about vibrations and controls. Five questions included in the survey were:

1. Did you find the simulation interesting?
2. Did you find the simulation realistic?
3. Did you feel that interacting with the simulation gave you an increased appreciation of the benefits/impacts of vibration control on real world systems (i.e. Safety, Efficiency, etc.)?
4. Did you feel that interacting with the simulation helped you to learn/understand the theoretical concepts being taught in class (i.e. Modeling, Dynamics, Vibrations, Control, Input Shaping, etc.)?
5. How good was this particular teaching tool as compared with others you have seen in courses at Georgia Tech (i.e. group projects, online lectures, student presentations, standard homework and lecture, etc.)?

The students were asked to respond to the questions by answering with a whole number between 1 and 5: 1 meaning a definite negative, 3 meaning neutral, and 5 meaning a definite positive. Twenty-six of the 46 students responded to the questionnaire. Their responses, shown in Table 1, give a good indication that this project was both enjoyable and educational.

V. REAL GANTRY CRANE

A real gantry crane in the Manufacturing Research Center at the Georgia Institute of Technology has been equipped with an input shaping controller. This will be used in the curriculum to reinforce what the students learn in class and experience in the MATLAB simulation. In addition, it will serve as a test bed for input shaping experiments.

A sketch of the crane is shown in Figure 1. The major components of the crane are the bridge, the trolley, and the control pendant. The bridge is an I-beam that moves forwards and backwards. The trolley moves left and right on the bridge. The hoisting mechanism, hoisting cable, and payload hang from the trolley. The crane has a

Table 1: Questionnaire Results.

	Question #1	Question #2	Question #3	Question #4	Question #5
Average Response	4.4	3.8	4.3	3.7	3.8

capacity of 10 tons. Its usable workspace is 2 stories high, 30 feet wide, and 100 feet long.

New hardware was added to the crane to implement input shaping. Figure 8 shows how the new hardware was installed and how it generates the input shaped signal. Button signals generated by the human operator travel from the pendant to the hoist controls or the bridge-and-trolley-control-box, depending on which buttons are pressed. In the bridge and trolley control box, a PLC (programmable logic controller) performs the input shaping algorithm and modifies the button commands. Figure 8 shows the button command entering the PLC and the altered command leaving the PLC. This command is then sent to the trolley and/or bridge motor drives. These drives use the incoming command from the PLC as velocity set points for the motors. To insure accurate execution of the PLC commands the drives are AC-AC inverters. This type of drive uses a pulse width modulated signal to accurately control the motors. In addition, in order to be compatible with the drives, the motors are inverter duty capable.

Figures 9a and 9b compare the shaped and unshaped responses of the crane. The data was taken by fixing a marker to the end of the crane and video taping its motion. This movie was imported into a computer and a MATLAB image-processing program calculated the markers position over time. Figure 9a shows that the payload oscillates while the crane is commanded to move and after it is commanded to stop. The hatched box represents approximately when the forward button was pressed on the control pendant. Figure 9b shows that input shaping eliminates these oscillations. This gives experimental verification of the benefits of input shaping and confirms the simulated results shown in Figures 2 and 3.

Students will be able to operate the crane with and without input shaping. This will give them a feel for how a real, industrial sized crane operates and show them the benefits of using input shaping on a real system. Obstacle courses, similar to those used in the simulations, will be set up and the students will drive the crane from a starting point to an ending point. Figures 10a and 10b compare how the crane moves through a sample obstacle course with and without input shaping. Notice that without input shaping, oscillations in the payload cause collisions with the obstacles. In addition, once the payload reaches its final destination it swings for several seconds. Figure 10b shows that input shaping eliminates these problems. When the students drive the crane they will observe these effects first hand. Future obstacle courses will be more complex and many paths will be possible. Similar to the simulations, student data will be used to examine how input shaping influences the type of path students take through an obstacle field.

In addition to these educational benefits, the crane will be used for experimental work in input shaping. Current research is underway to find input shapers that optimize move time and robustness to modeling errors. For example, Figure 11 compares the response of two types of shapers; a ZV and UM-ZV shaper. A ZV (zero vibration) shaper [4, 5] is the simplest input shaper and

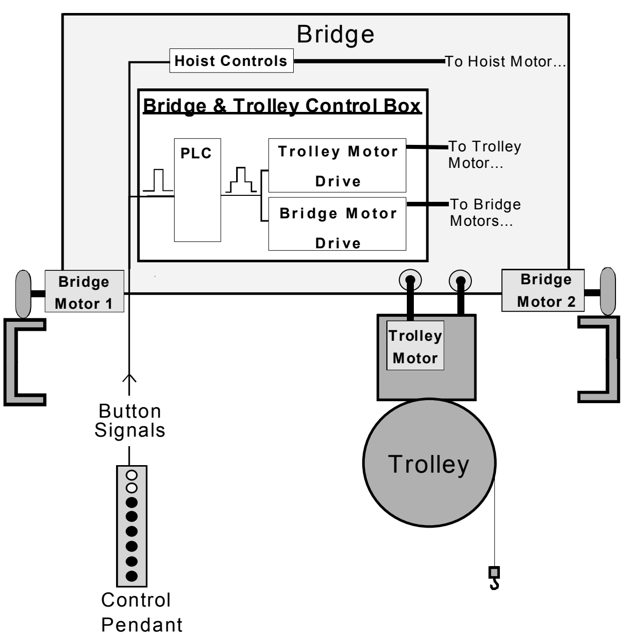

Figure 8: Hardware Implementation of Input Shaping on Crane.

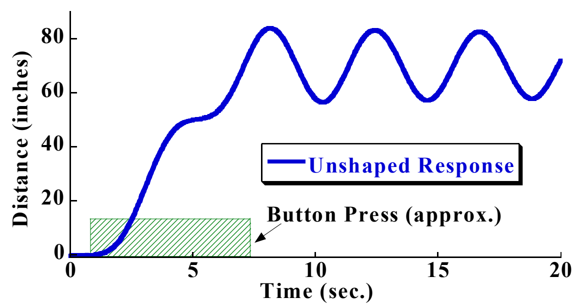

Figure 9a: Experimental Data: Crane Response without Input Shaping.

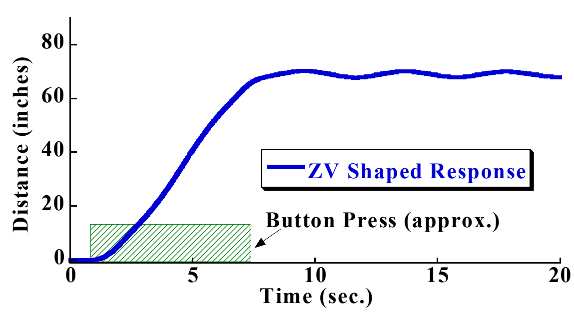

Figure 9b: Experimental Data: Crane Response with Input Shaping.

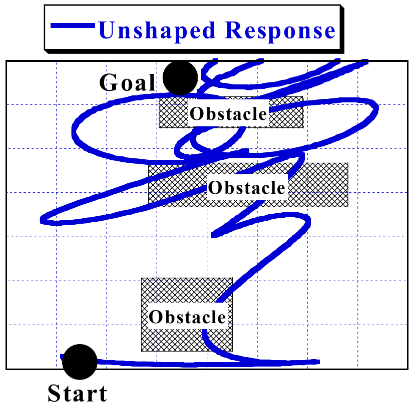

Figure 10a: Experimental Data - Obstacle Course Without Input Shaping.

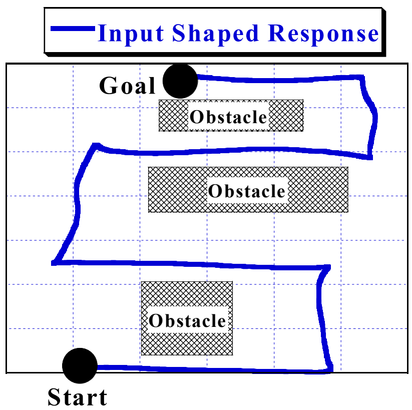

Figure 10b: Experimental Data - Obstacle Course With Input Shaping.

was presented in the Introduction. Notice, Figure 2 shows that ZV shapers only use two impulses. A UM-ZV (unity magnitude zero vibration) shaper [6] uses three impulses to generate the command. Similar to the ZV shaper, the impulses are timed such that the response has zero vibration. The benefit of a UM-ZV shaper is that it generates a much faster response than the ZV shaper. Figure 11 shows that the UM-ZV response accelerates and decelerates the payload much faster than the ZV response. In addition, Figure 11 shows that the increased speed of the UM-ZV allows the payload to travel a longer distance over the same amount of time. This improvement in overall speed would help streamline moving operations and cut costs in industrial settings.

VI. CONCLUSIONS

Several novel approaches were developed to effectively teach crane dynamics and control design in the undergraduate system dynamics and controls course at Georgia Tech. Homework problems, interactive computer

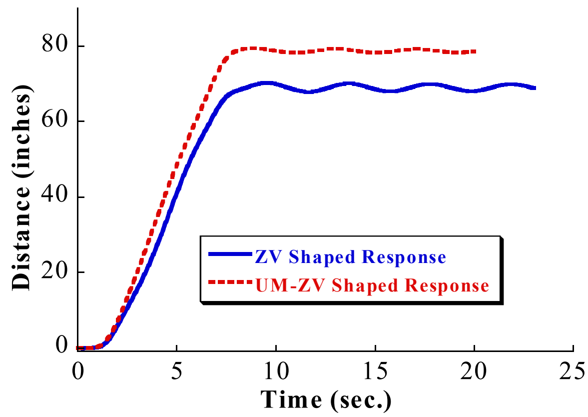

Figure 11: Experimental Data: ZV vs. UM-ZV Input Shaper.

simulations, and, in the future, real cranes are being utilized as teaching aids for this class. In addition to teaching, the way in which students control the cranes, both simulated and real, will be studied to see the effect that input shaping has on the decisions made by crane operators. The real crane will also be used for the experimental verification of new input shaping designs.

VII. ACKNOWLEDGEMENTS

This project would not have been possible without the generous support of Siemens. They provided the technical support and physical hardware necessary to implement input shaping on the gantry crane.

VIII. REFERENCES

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