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ABSTRACT

Transportation of objects using overhead cranes can induce pendulum motion of the object, which usually must be damped or allowed to decay before the next process can take place. Recent work at Sandia National Laboratories (SNL) has shown that oscillation damped transport and swing-free stops are possible by properly programming the acceleration of the transporting crane. This paper reviews the theory associated with oscillation-damped trajectories for simply suspended objects and describes a specific, full-scale implementation of the damped oscillation methods for the Oak Ridge National Laboratory (ORNL) Advanced Integrated Maintenance System (AIMS). Hardware and software requirements and constraints for proper operation are discussed. Finally, test results and lessons learned are presented.

I. INTRODUCTION

SNL and ORNL have recently been investigating the use of intelligent machines for nuclear waste-handling operations. One particular mode of operation requires that various heavy objects such as storage casks be moved from location to location within a facility. Typically, the transported object would be lifted by a crane hook on the end of a cable, creating a pendulum free to swing during transit. This swinging motion makes remote positioning of casks difficult to control precisely and is potentially destructive to hot cell equipment and other storage casks. Therefore, a typical crane operator must move slowly and allow time for oscillations to damp out before proceeding to the next step in a given operation.

Algorithms for damped-oscillation, swing-free transport of suspended payloads have been developed by Sandia, and testing has been successfully completed using a CIMCORP XR®6100 gantry robot, a 50-lb weight, and an 80-in. cable. However, a desire to carry out a full-scale test has led to the use of facilities available at the Oak Ridge National Laboratory.

The Advanced Integrated Maintenance System (AIMS) is an engineering and operations testbed developed for remote maintenance and handling studies within the Consolidated Fuel Reprocessing Program (CFRP) at the Oak Ridge National Laboratory. The goal of CFRP has been to advance the technology of in-cell systems planned for future nuclear fuel cycle facilities. AIMS has provided the capabilities to examine the needs and constraints necessary for hot-cell remote maintenance and includes a force-reflecting master/slave teleoperator, the advanced servomanipulator (ASM), and an overhead transporter system. The associated control system provides a flexible programming environment conducive to controls experimentation. In order to implement the damped-oscillation, swing-free algorithms on the AIMS transporter (crane), shown in Fig. 1 as the P&H crane in the background, the ASM has been replaced with a load-testing fixture to provide a pivot point for the pendulum.

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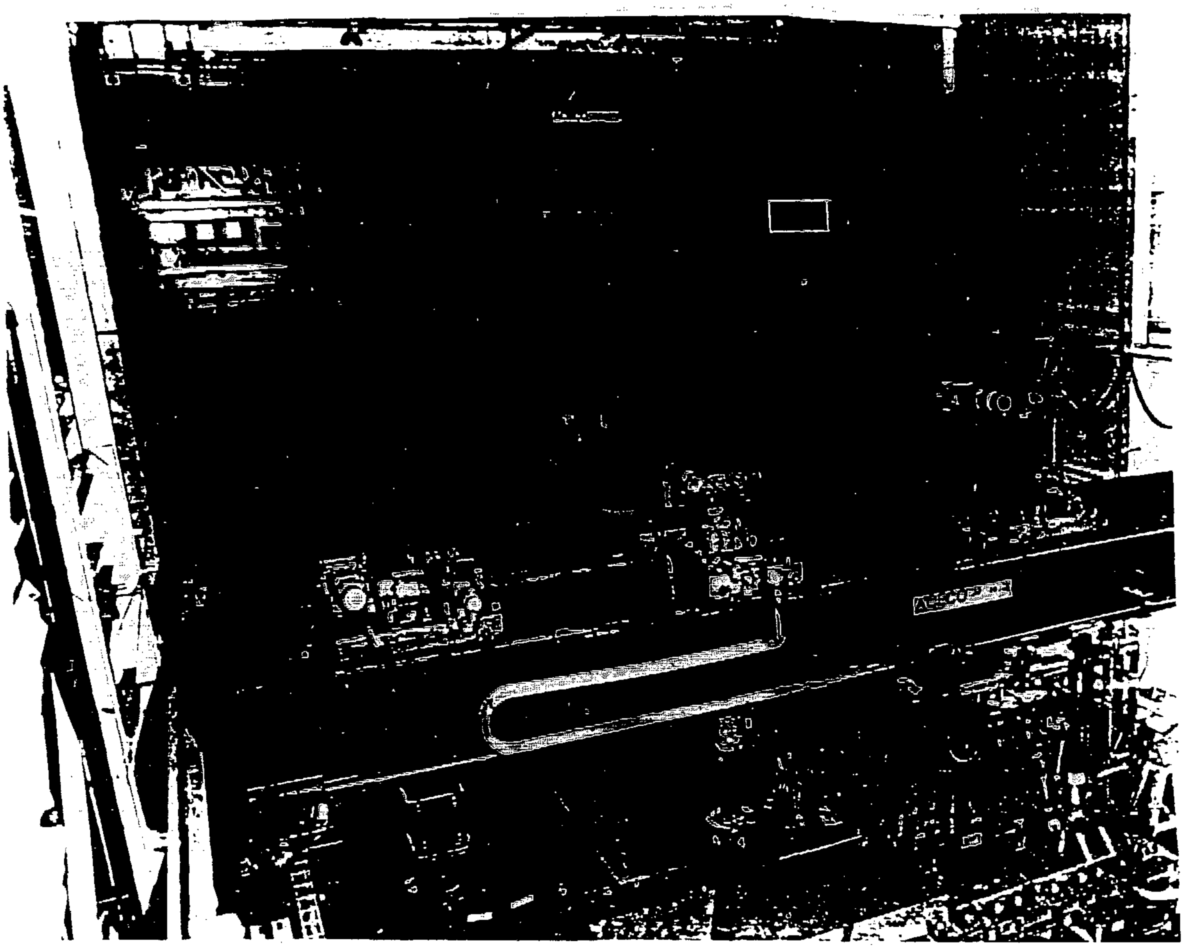

Fig. 1. AIMS Crane in Background

MATHEMATICAL FOUNDATION FOR AMP[illegible] OSCILLATION CONTROL

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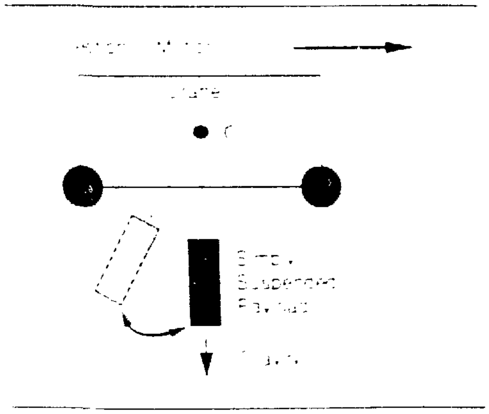

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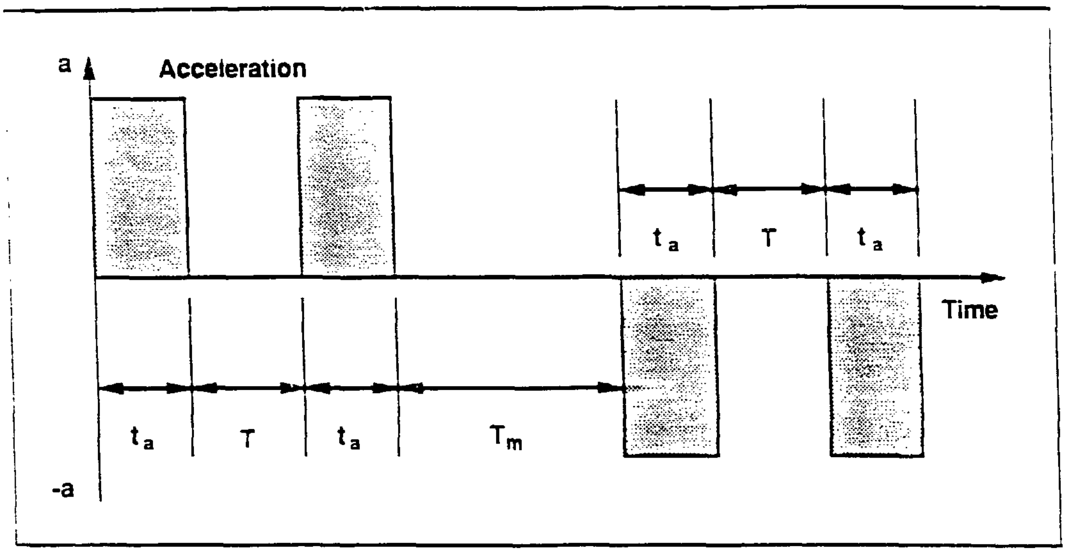

Fig. 3. Acceleration Profile for Damped Oscillation.[1]

that the oscillation imposed on the object due to the second duration of acceleration is 180° out of phase with the initial oscillation of the swinging object, resulting in the object moving at constant velocity without oscillation after the second acceleration. After an arbitrary length of time, the same procedure is applied to the object to produce deceleration for an oscillation-damped stop. The objective is to determine the values of T and t_a that yield fully damped oscillation movement.

If θ is defined as the angular displacement and ω_n as the natural frequency of oscillation, then the oscillating motion of a pendulum may be represented by a second-order nonlinear differential equation with constant coefficients[2-4],

$$\ddot{\theta} + \omega_n^2 \sin\theta = 0 .$$

Large angles of displacement would require an exact solution, which is unsolvable in terms of elementary transcendental functions because an elliptic integral is involved.[1] However, for relatively small angles of displacement a linear approximation is possible, yielding

$$\theta = \alpha \sin\left(2\pi \frac{t}{\tau_0}\right),$$

for α defined as the amplitude of oscillation and τ_0 defined as the period of oscillation of the pendulum for small amplitudes. For large amplitudes of oscillation, nonlinearities may be grouped into the period of oscillation, creating an approximate solution

$$\theta = \alpha \sin\left(\frac{2\pi}{1 + \left(\frac{\alpha^2}{16}\right)}\left[\frac{t}{\tau_0}\right]\right) .$$

For the acceleration profile given in Fig. 3 and the nonlinear approximation for the differential equation of the swinging pendulum, the constant velocity time, T, may be defined as a function of acceleration time, t_a, and approximations for τ_T (pendulum period including nonlinearities during constant velocity) and τ_{t_a} (pendulum period including nonlinearities during constant acceleration), which in turn are expressed as functions of the ratio of crane acceleration to the acceleration of gravity (a/g). This relationship produces the following equation:

$$T = \frac{\tau_T}{\pi} \tan^{-1}\left[\frac{\tau_T}{\tau_{t_a} \tan\left(\frac{\pi t_a}{\tau_{t_a}}\right)}\right] .$$

From this equation, a surface defining the values of T and t_a for all a/g ratios is created. An examination of this surface reveals that for the relatively low acceleration levels likely to be found in large, high-capacity overhead cranes, the a/g ratio is very small and the nonlinearities may be neglected. The remaining limits for acceleration time, t_a, are 0 and 0.5. The 0 limit requires an impulse acceleration and is therefore impractical to implement. The 0.5 limit produces an acceleration time of 0.5 times the pendulum period, followed by a constant velocity time of zero and then followed by another constant acceleration time of 0.5 times the period, conveniently reducing to a constant acceleration time equal to the period of the swing of the pendulum without an interim constant velocity time, T. The final acceleration profile shown in Fig. 4 defines the simplest swing-free motion with an initial constant acceleration period equal to the period of the pendulum, followed by a constant velocity segment transitioning the desired motion, and finally stopping at the required position through a deceleration profile equal but opposite to the original acceleration profile. This profile has been implemented on the AIMS crane.

III. IMPLEMENTATION

The AIMS control hardware utilized for swing-free software development consists of 15 single-board computers divided among 7 Multibus I backplanes.[5] Four out-of-cell control racks are interconnected with a fiber optic local area network. A man-machine Interface (MMI) rack handles video switching and color graphics touch screen interfacing, and controls the system hard disk and local area network. An auxiliary control system (ACS) rack provides positioning of the heavy equipment within the facility–the overhead manipulator transporter and 20-ton crane as well as facility camera control. Calculations for each master/slave manipulator are accomplished in the two master racks by five cpu boards acting in parallel in each rack. Three additional "slave" racks in the high bay/hot cell mockup provide smart data acquisition systems for the ACS and master racks communicating through dedicated fiber optic links.

AIMS software, written in multitasking ®polyFORTH, includes the actual real-time controls, a graphics package, and a custom local area and control network (LAcN). Two 20-Mbyte hard disks provide adequate memory to store both operations and experimental software. Modifications for experiments therefore can be made easily without corrupting operational software. Most of the functions are controlled through menus with the exception of teleoperation, crane motion, and overhead transporter motion, for which status menus provide important information to the operators.

Implementation of the oscillation-damping algorithms for AIMS has required significant modification to the existing controls software. Transporter motion normally is initiated through the use of the hand-held pendant operating in an open-loop velocity control mode. Transporter

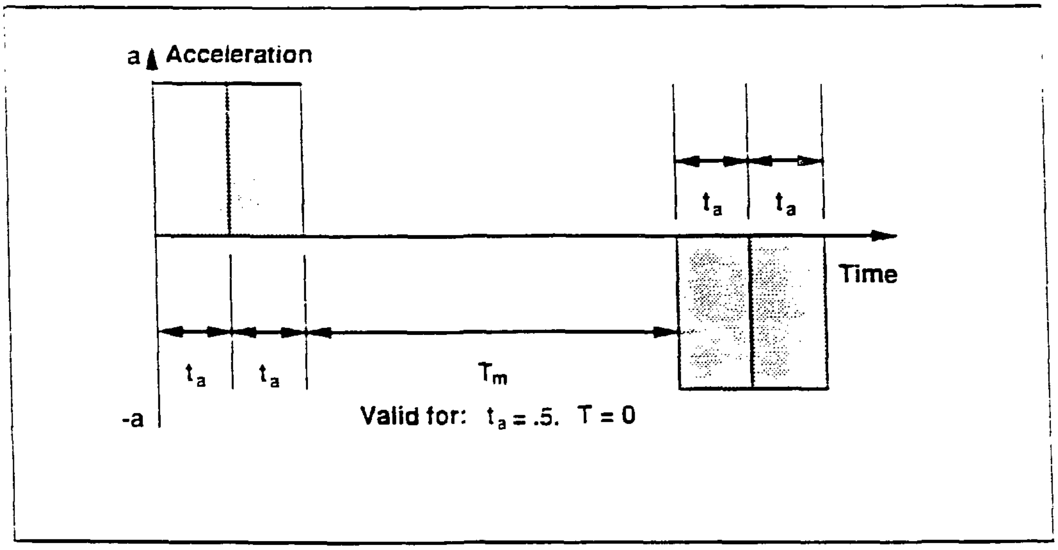

Fig. 4. Acceleration Profile for a/g Small.

position sensor data are provided, but only as status information for the operator. The damping algorithms as developed by Sandia require closed-loop positioning and robotic motion, trajectory planning, and programmable acceleration profiles, none of which originally existed in the AIMS transporter control scheme. All software development for the swing-free demonstration has been implemented on the ACS rack code on the hard disk devoted to development, allowing either the swing-free code or the normal operating software to be loaded.

The ACS rack that controls the crane normally communicates to the operator via graphical menu touch screens, but a VT100 terminal also is available for debugging purposes and engineering-level code development. The crane slave rack located on top of the crane runs ROMed code only and acts as a smart data acquisition system, functionally providing remote I/O. The ACS and slave racks are connected by 1-Mbaud serial communications cards linked by glass fiber optic lines. Data packets are exchanged at a closed-loop level of 100 Hz. Control algorithms, run on the ACS rack, have (buffered thru the programmable controller originally provided by P&H) access to ±10VDC servoamplifier inputs, converted binary coded decimal resolver positions, and servomotor enables, brakes, and status indicators. The programmable controller has been maintained in the system to provide an emergency backup in the event of a computer failure and is not used for any control functions. However, maintaining the programmable controller in the system has required that the two bridge motors (one driving each end of the crane bridge) be paralleled off the same servoamplifier because the original hardware does not have the control intelligence to drive separate motors on a flexible bridge. While this configuration provides very smooth bridge motion, independent motion of the bridge ends for precise positioning can not be supported. The resolver resolution is 0.0625 in./count for the bridge motion and 0.0625 in./4 counts for the trolley motion. While this normally is not acceptable resolution for robots, it has proved adequate for a large facility, especially since the two ends of the bridge do not track exactly. Tests have shown that position deviation due to bridge flexing is typically ±2 in.

Control algorithm software has been written to run on top of existing application software so that either the hand-held pendant controller or robotic positioning may be used. The communications software remains intact with the crane servoloops closed at the 100-Hz rate. The system clock interrupt is used to synchronize a 20-Hz increment for the damped-oscillation trajectory planner. The trajectory planner simply consists of three segments: The first segment is a constant acceleration ramp up to a constant velocity second segment, and the third segment is a constant deceleration to stop at the desired position. All accelerations and decelerations must be synched to the period of the swing of the pendulum. Starting from current resolver position and heading toward a specified goal position, the position is incremented at a prespecified constant rate of acceleration for the period of oscillation. When the acceleration period is over, the last actual velocity (delta position) is measured and used as the constant velocity increment during the middle leg of the motion, providing a smooth segment transition. Then the difference between the transition position and the starting position is computed and subtracted from the goal position to identify the deceleration ramp-down start position. When this position is reached, constant deceleration with the same magnitude as the initial constant acceleration ramp is started for the length of the period of swing. A tolerance is placed around the goal position so that it will be the end point in the trajectory.

IV. RESULTS AND CONCLUSION

For testing and demonstration purposes, a fixed pendulum was fabricated using a 27-ft cable and lifting fixture for a 55-gal drum filled with sand, which weighs ~900 lbs. The total length of the cable, lifting fixture, and drum was 32 ft. The pendulum was then installed on the AIMS load-testing fixture on the crane. The period of swing was measured and determined to be 6.1 s in good agreement with the theoretical period of 6.14 s for a simple pendulum. A U-shaped path with additional drums for obstacles at the corners of the U and a set of scales at the endpoint provided the test environment. The drum was first lifted from among an array of drums. The U-shaped path was then followed to the scales, where the drum was lowered for weighing. The drum was then picked up and returned to its original location.

Extensive repetitive runs have shown that this particular implementation of the damped-oscillation algorithms consistently resulted in less than ±0.5 in. of residual swing, allowing the drum to be set down on the scale and maneuvered in tight situations without any difficulties. The variation in residual swing is believed to be related primarily to the errors in positioning caused by the bridge flexing. Robotic positioning done as a control case with no damped-oscillation control has produced up to ±3 ft of oscillation. (This is totally dependent on where the crane stops with respect to the swinging pendulum.) As an additional data point, hand-held pendant AIMS operation typically produces up to ±1 ft of pendulum swing.

Also, several crane design issues that affected performance have been identified. The AIMS crane does have servomotor positioning (as opposed to typical induction motor driving), which is essential to swing-free operation. However, the most important variable is that the servoamplifier/servomotor/gearbox combination be properly sized for the necessary swing free-operation on a system on which bridge inertia is significant. On the AIMS crane, the highest velocity and acceleration possible were still disappointing. Adequate position sensing and resolution must be considered. Finally, bridge drive control schemes that account for mechanical flexibility also must be provided before acceptable oscillation-damped motion and robotic positioning for large facilities can be successful. Even though the AIMS crane and controls were not designed with damped-oscillation capabilities in mind, this implementation did successfully demonstrate the oscillation-damping algorithms on a full-scale crane.

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