Isolator Base: Seismic Damage Mitigation for Museum

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SEATTLE ART MUSEUM
ELECTRICAL & COMPUTER ENGINEERING

Research Question

How would you use an active system to prevent damage to artwork from ground movement like in an earthquake?

Red-figured Amphora (two handled vessel) with Herakles, Amazons and Warriors
late 4th century B.C.
Ceramic,
Greek Apulia (modern Southern Italy)
Classical Period
38 in. (96.5 cm) Diam.: 51 in
(Photo by: J. McIntyre)

Figure 1: Arrows indicate "weak" points in sculpture areas may break in seismic event

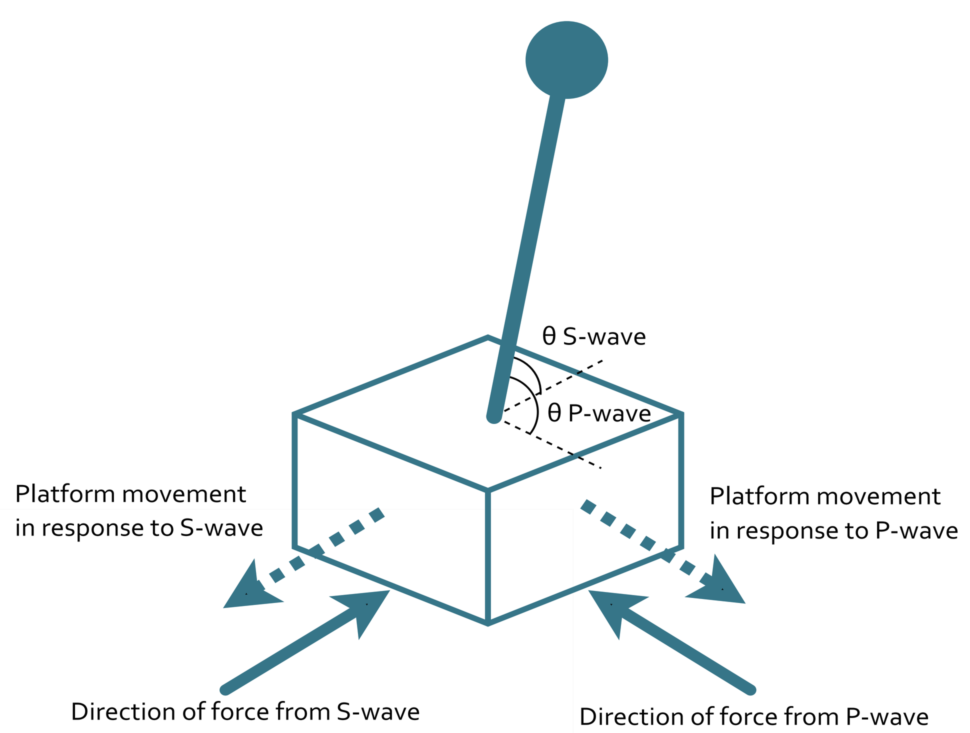


Figure 2: Model of object platform with P-wave and S-wave forces as inverted pendulum

Background

The tall top heavy nature of art objects, with multiple stress points, present a unique challenge for stabilization during seismic events like earthquakes. Current methods require special rigging of an object to the environments structure or the development of passive systems specifically designed for the object. The project is to design and develop an active system that will be able to stabilize a nonspecific object using sensors and motors in a precise way.

Below is an overview of design requirements of the platform, some which are unique to a museum environment:

- Cost of system should be relatively low to ensure affordability
- The platform should be able to isolate an object from earth movements corresponding to a magnitude 6.0 earthquake on the Richter scale (forces up to .25 g's, 2.45 m/s² or .024 N)
- Minimal impact to the immediate environment of the object:
  - Should not introduce any environmental change that might adversely affect an art object

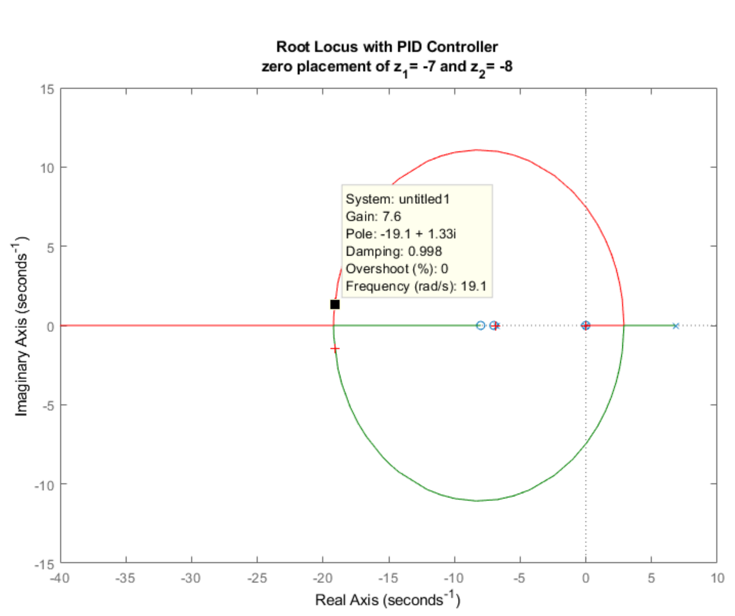


Figure 3: Root locus of control system, displaying the zeros and poles

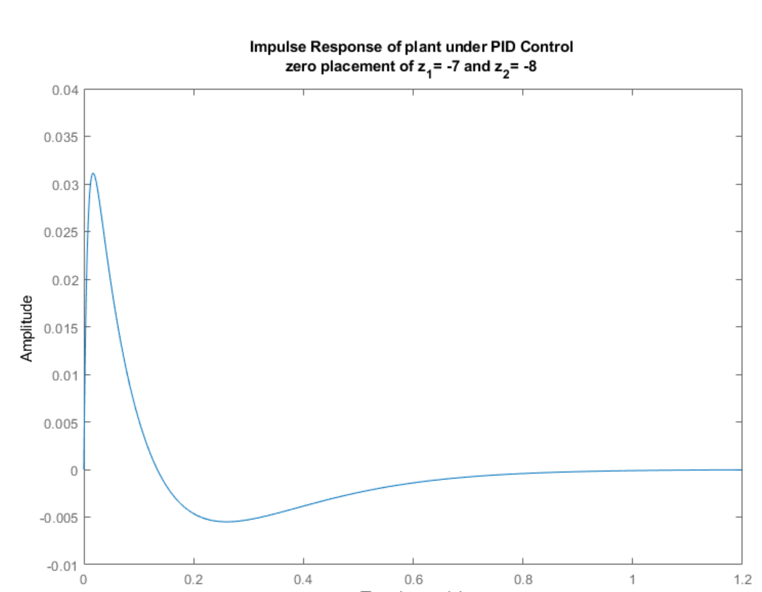


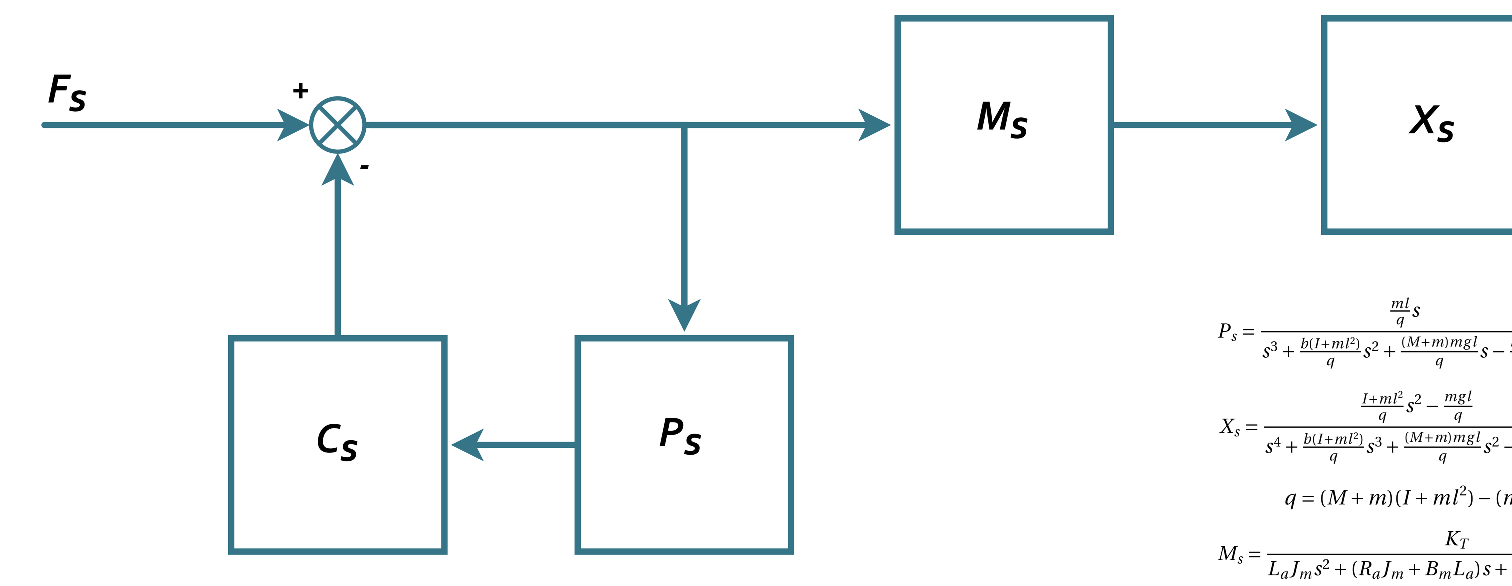
Figure 4: Impulse response of control compensate on object

Methodolgy

- Seismic waves can be very complex. Focusing on the longitudinal Primary waves (P-waves) and transverse Secondary waves (S-waves) of surface earthquakes makes analysis of ground movement and the influence of the ground movement on objects more approachable
- By focusing on two primary axis of motion, an object in a seismic event can be modeled as an inverted pendulum moving through both the P-wave and S-wave dimensions
- The inverted pendulum model becomes a well defined system where a control effort can be designed to respond in a specific manner to the external forces of ground movement
  - The platform can consist of a base which is secured to the ground; the object to be stabilized attached to a movable sled, which is part of the platform
  - The interaction of the platform, sled and object to a seismic event can be modeled by a set of equations
- A Proportional plus Integral plus Derivative (PID) control compensate will provide the necessary precise sled movement to isolate the object from ground movement
  - A PID controller reduces overshoot and time to steady state of platform
  - The root locus design method provides the control equation constants which allows for stabilization of a range of objects

Results & Discussion

- The modeling of an object and platform as an inverted pendulum adequately describes system behavior in seismic context
- Due to the nature of a generalized control equation, the platform is able to successfully stabilize objects with similar defining characteristics
  - For stabilization of objects outside of controller range, control compensate will need to be recomputed
- Low power consumption is achieved through use of digital low pass filtering to reduce input noise. During periods of nominal seismic activity no control effort is provided and system is passive
  - When in active phase of seismic isolation, power consumption spikes. Spike is result of necessary motor drive (power and acceleration)
- System can be implemented with standard, readily available materials. Although readily available materials reduce cost of system, aesthetic and performance compromises must be made



$$P_s = \frac{\frac{ml}{q}s}{s^3 + \frac{b(I+ml^2)}{q}s^2 + \frac{(M+m)mgl}{q}s - \frac{bmgl}{q}}$$

$$X_s = \frac{\frac{I+ml^2}{q}s^2 - \frac{mgl}{q}}{s^4 + \frac{b(I+ml^2)}{q}s^3 + \frac{(M+m)mgl}{q}s^2 - \frac{bmgl}{q}s}$$

$$q = (M+m)(I+ml^2) - (ml)^2$$

$$M_s = \frac{K_T}{L_a J_m s^2 + (R_a J_m + B_m L_a)s + (K_T K_E + R_a B_m)}$$

$$C_s = \frac{(s+z_1)(s+z_2)}{s} = K_P + \frac{K_I}{s} + K_D s$$

Figure 5: Control block diagram and corresponding transfer functions:
F_s - seismic force, P_s the object, C_s the control algorithm, M_s the sled drive motor, X_s the movement of the sled

Conculsion & Future Investigations

It is possible to develop a platform that can actively isolate an object with a high center of gravity from seismic events. Modeling the object and platform as an inverted pendulum is foundational to working with the complex nature of ground movements and how ground movements affect objects. From the initial implementation of the seismic isolator, there are additional areas for investigation:

- Improvement and development of cooling system to ensure minimization of system heat production on the object's environment
- Determine if error feedback will substantially improve control response of system
- Integration of hardware to track sled position to confirm software position tracking and to reduce potential system failure
- Include monitoring and communication system
  - User interface to program based on object's characteristics
  - Provide information of seismic events and system performance to events
- Further refinement of control compensation
  - Development and implementation of compensator that will provide more precise control effort based on specifics of object to isolate
- Investigate platform cost when implementing scaling of platform for larger objects and aesthetic improvements

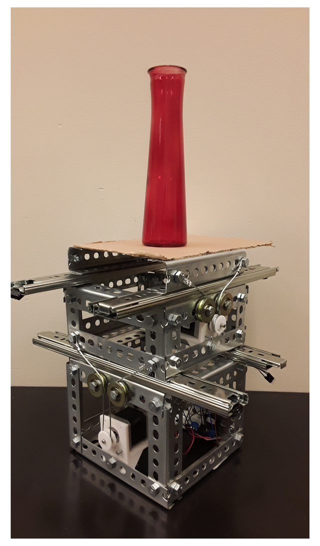


Figure 6: Prototype of Isolator Base platform. Motor drive in transverse and longitudinal axis of ground movement

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