

Robotic Swing Drive as Exploit of Stiffness Control Implementation

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2001 Florida Conference on Recent Advances in Robotics

ABSTRACT

A foundational model in robotics control, the pendulum or swing, modeled here as a simple harmonic oscillator, can yield effective and useful linear control behavior even with incomplete implementation. Active, augmentative, deflection-related torque alone, without velocity-related torque, is sufficient to generate and maintain useful oscillations of contained amplitude within the context of greater inherent elastic restraint.

INTRODUCTION

The pendulum model, both in its inverted form and in the non-inverted or swing form, is recognized here as a useful general basic model employable by analogy to all dynamic robotic tasks of similar order, including balance and aspects of locomotion and manipulation.

The implementation embodied here constitutes a simple case, in which the inherent passive stiffness (elastic resistance to deflection) of the system is overcome in a limited region by actively exerted, augmentative, deflection-related torque.

This implementation does not include any active velocity-dependent torque capability.

Deflection-related torque generally affects stiffness, and therefore frequency of oscillation. Velocity-related torque changes the energy of the system, and so generally affects the amplitude of oscillation.

Before we discuss our simplified model, we refer to the optimum theoretical approach to modeling and controlling simple harmonic oscillating systems.

Theoretically, the best method of driving oscillations in such a system is by means of actively applied, deflection-augmenting, velocity-related torque - referred to here as driving torque.

Theoretically, the best method for increasing the frequency of oscillation is by increasing the stiffness. This can be done through active deflection-related torque application to augment the inherent passive stiffness of the system. This torque can be referred to as stiffening torque.

Both driving and stiffening torque can be applied as described above, or in the reverse sense. The deflection-related torque may be applied to counteract inherent stiffness, making the system behave as though it were less stiff. Similarly, the driving torque can be applied in a negative sense, to reduce the amplitude, instead of augmenting it.

In the theoretical approach, we would configure the system with passive elastic deflection restraint such that the inherent stiffness is consistent with the desired oscillating frequency. No active energy expenditure is generally needed to maintain desired frequency in this approach, except as occasionally required to induce some small and temporary deviation from the inherent frequency.

To drive oscillations, we would measure the angular swing velocity and exert a deflection-augmenting torque proportional to this velocity.

Such is the power of the general theoretical approach, although it requires the measurement of both position and velocity, and the calculation of respective torques proportional to each. The processor resources and additional sensing requirements add cost to this approach.

Our simplified approach, while recognizing the value of the theoretical optimum, seeks to generate useful and satisfactory results without the technical complication of the full theoretical implementation.

We show that useful results can be obtained even when only the simpler, deflection-based torque is applied.

In this modified approach, we need not measure velocity, only position. A region of deflectional instability about the resting position is induced by application of deflection-augmenting torque proportional to displacement.

This means that if the swing is displaced a small amount from the vertical, torque will be applied to actively increase this deflection. This active effect compounds, since as the torque is applied the swing is displaced even further, giving rise to even greater applied torque, and so the swing is displaced further still.

Eventually a point is reached where the servo is overpowered by inherent elastic restraint (gravity acting to swing the pendulum back), or the servo runs into its limit of travel, and so can exert no additional torque.

At this point, the swing begins to return, swinging back through the zero point and continuing to the other side, where similar corresponding activity takes place. In this way the swing amplitude is continually increased until a balance is achieved between applied power and inherent elastic restraint (gravity).

By adjusting the gain, or proportionality between deflection and servo torque, the amplitude of the resulting oscillations can be adjusted.

Limitations in the system, including servo delay and inertia, and limits of travel, affect the operation of such a system.

The servo cannot respond immediately to a change in signal, as there is some real time delay involved. Also, if the servomotor is turning rapidly, its own inertia must be overcome before it can stop and reverse direction. This same inertia is a factor as the motor accelerates from rest.

The servo as presently configured is limited in its angular travel to slightly under ninety degrees in either direction from the center value.

The commands to the servo must keep the desired servo position within these travel limits.

In this configuration, the predominance of these effects throughout the swing cycle appears favorable for our purposes. The delays shift the phase of the applied torque with respect to the swing angle, and thereby may cause the applied action to have more of a driving effect.

This would be consistent with our expectations, since in oscillatory motion, the velocity is phase delayed by ninety degrees. Since driving is theoretically proportional to velocity, any phase shift or delay effect with respect to position contributes more to driving, in either a helpful or adverse sense depending on conditions. It may be possible to alter these delays to further modify the driving effect in useful ways.

Insofar as these delays due to non-ideality shift the effect towards driving, we do not object, nor would we seek to minimize these system characteristics.

In the course of the swing cycle, the servo arrives at its limits at the most opportune times in the cycle, and this also is advantageous to driving, which is our objective.

At the extremes of swing amplitude, the servo travels from one limit to the other, and so is always configured to apply its full torque to greatest effect. This is another synergistic system quality.

It would be a matter of future study to determine if implementation of actual driving by velocity-related torque would significantly improve system performance, and to what degree such refinement can be correlated to actual observed behavior of similar real world systems.

The power of this simplified method is in the ability to induce oscillations in analogous robotic systems. A swinging or waving arm or walking leg, flapping wing, waving antenna or flag, or any similar robotic structure whose chief function is to oscillate can be simply and effectively excited to do so by suitable adaptation of this simple method.

The advantages are those of simplicity and fortuitous real world synergism, where non-idealities are recognized as working to our favor, and added complexity for simple applications might not even be necessary.

PLATFORM MECHANICS

The SwingBOT apparatus can be best understood as functionally modeling the familiar example of a child swinging on a swing.

If the swing is at rest and the child in the swing remains motionless, no torque is induced on the system and the swing remains at rest.

Once the child starts to move the legs and upper body, a torque is induced on the system and the swing begins to oscillate. The child can increase the amplitude of these oscillations by moving the legs and upper body so as to induce a torque on the system that leads the phase of the swing itself by 90° .

Conversely, the child can decrease the amplitude of the swing's oscillations by inducing a torque on the system that lags the phase of the swing by 90° .

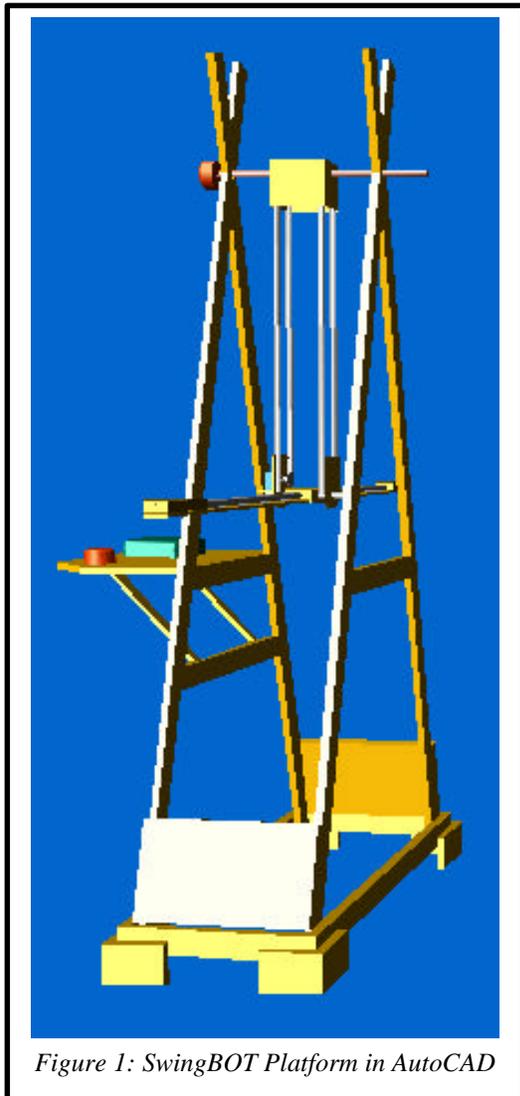


Figure 1: SwingBOT Platform in AutoCAD

PLATFORM CONFIGURATION

The simple non-inverted pendulum consists of the following:

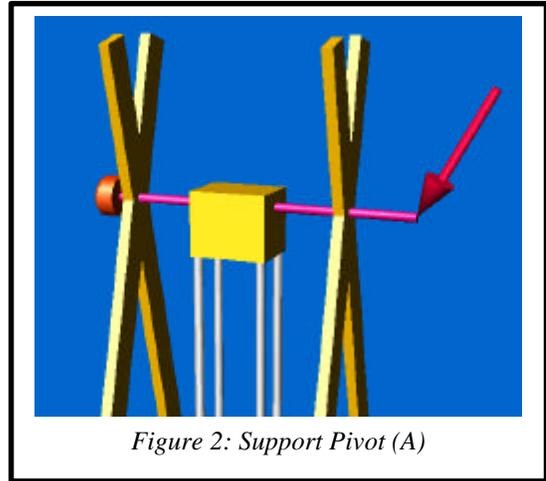


Figure 2: Support Pivot (A)

- A) a support pivot, (the top of the swing, from which the rest of it swings) being a horizontally oriented rod constrained to allow only rotation about its longitudinal axis,

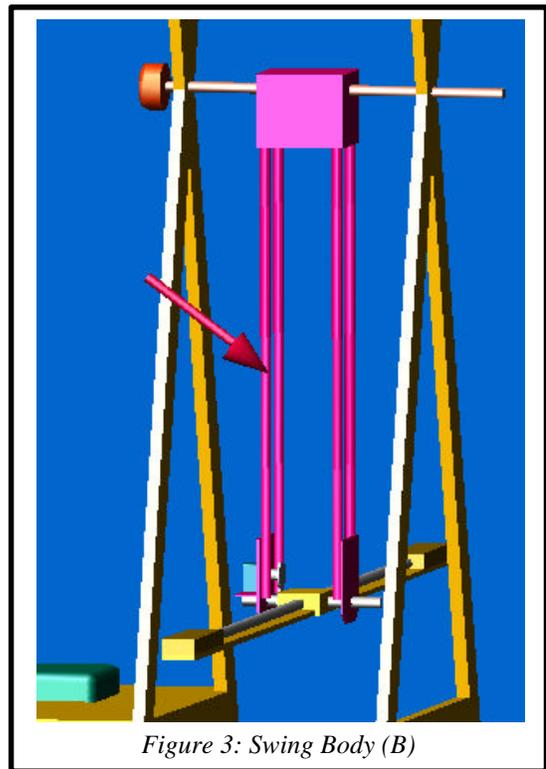


Figure 3: Swing Body (B)

- B) a first linear structural element perpendicularly attached to (hanging from) the support pivot and thereby constrained to allow only rotation in a vertical plane about the horizontal pivot axis (swinging), and

- C) a second linear structural element (crossbar), being attached to the first linear structural element by constraint (crossbar pivot)

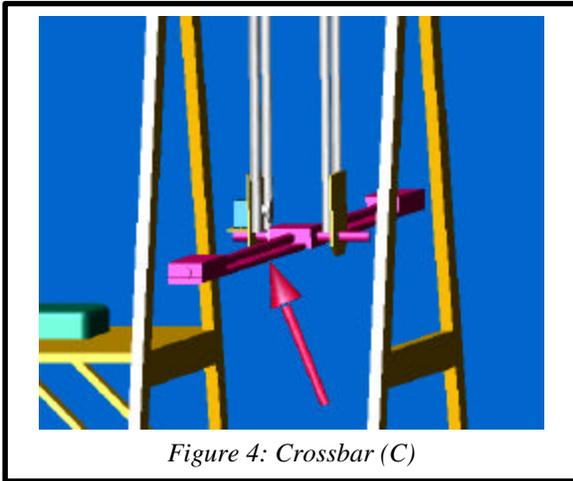


Figure 4: Crossbar (C)

allowing only rotation in a vertical plane (see-sawing) about a crossbar pivot axis oriented parallel to the support pivot axis (top) and displaced some distance (bottom of the swing). The crossbar is actuated by

- D) a servomotor responding to the actions of

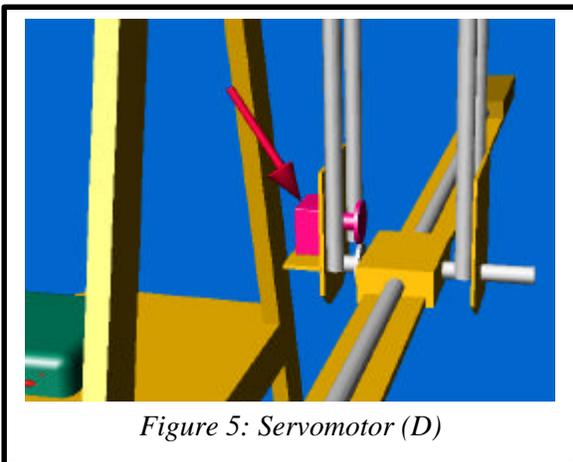


Figure 5: Servomotor (D)

- E) a controller using inputs from
- F) an angular position sensor mounted suitably with respect to the support pivot axis and
- G) a gain selector configured for operator input.

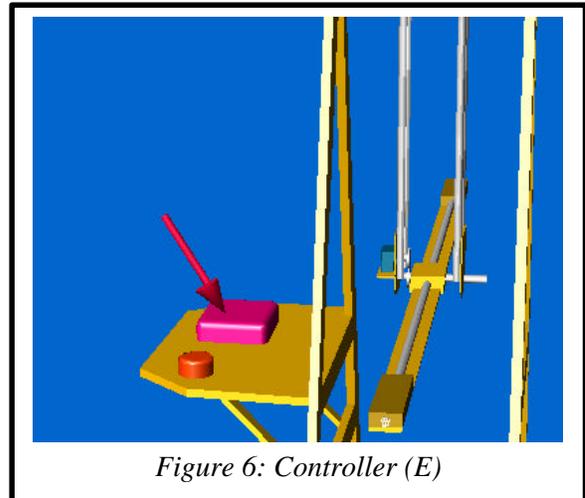


Figure 6: Controller (E)

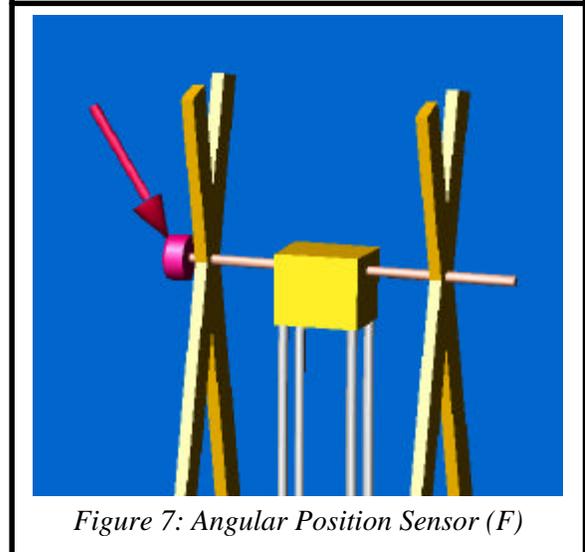


Figure 7: Angular Position Sensor (F)

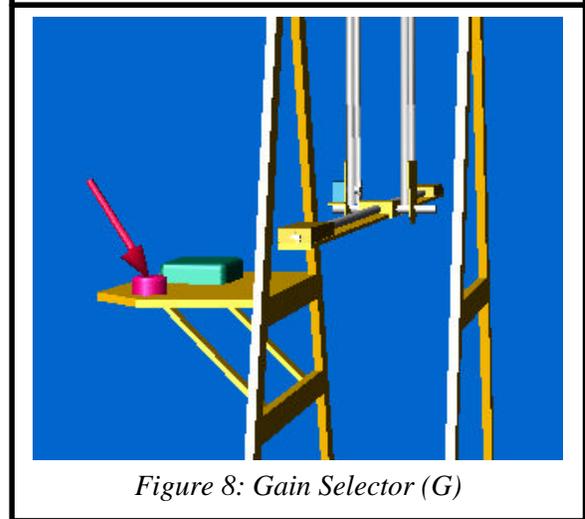


Figure 8: Gain Selector (G)

We refer again to the case of the case of a child swinging on a swing:

The support pivot (A) is the top of the swing-set, from which the rest of the swing is suspended.

B above is the hanging swing structure that hangs the chair from the support.

C above is the child seated in the chair, who exerts torque by holding on to B, while effecting dynamic body and leg motions through motor action (D), to excite the swing system into desired oscillations.

The controller (E) is the brain of the child, which senses parameters related to swing amplitude (F), and chooses appropriate desired gain (G). These values are processed to calculate and effect the motor action (D), which drives the body and legs to exert torque, thereby driving the swing.

In the SwingBOT, the support pivot (A) is mounted atop a wooden dual A-frame structure resting on the floor for support. The Pivot axis is oriented horizontally at the top of the A-frame structure, extending between the peaks of the two A-frame trusses comprising the support structure.

The pendulum and crossbar swing from this support axis. The controller, with its associated power supply, occupies a shelf partway up the outside of one of the A-frame trusses. Ribbon-wires connect power and signal to the servomotor and two potentiometers. One potentiometer is mounted along the pivot axis atop the A-frames to determine swing position angle, and the other receives manual input to implement desired gain.



Figure 9: SwingBOT Mechanical Platform

PLATFORM ELECTRONICS

PROCESSOR

The processor is a Motorola 68HC11. It is installed on a MTJPRO11 board from Mekatronix. The 8-bit processor is operated in expanded mode at 2MHz with 32K external SRAM. The internal processor hardware used in this project includes the A/D Converter and Output Compare subsystems.

The HC6811 contains an 8-bit Analog-to-Digital converter. There are eight individual inputs to the system, which takes 16µs per conversion. The Output Compare system allows timer-driven interrupts based on a 16-bit free-running counter. This hardware system allows pulse-width modulated (PWM) waveforms to be generated using interrupts.

The software for this project was developed using the ImageCraft C compiler for the 68HC11.

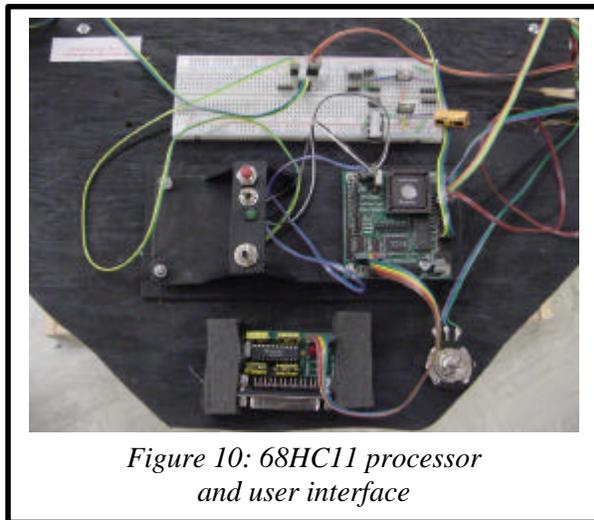


Figure 10: 68HC11 processor and user interface

SENSORS

The swing uses three sensors during operation.

A 1K potentiometer is used to measure the deflection angle of the swing from the resting position (Angle POT). The outer pins are connected to Vcc and GND to create a voltage divider output with the center contact. This voltage is read using the 8-bit A/D converter hardware inside the 68HC11. This results in an angle resolution of approximately 1degree.

Another 1K potentiometer is used to determine the open-loop gain of the motor output (Gain POT). This is a user input that can be varied during operation. A similar voltage divider circuit

is read using the A/D converter to determine this desired gain.

A Single-Pole, Single-Throw switch is connected to one of the 68HC11 digital inputs. This is a user input to determine if the crossbar will be driven to increase or decrease the amplitude of the oscillations (Mode Switch).

MOTOR

A Cirrus CS-80 servomotor controls the position of the crossbar. The rated stall torque is 343 oz/in. The position of the servo is determined by the positive width of a 50Hz PWM signal. The positive pulse width for the center position is 1550µs. The PWM signal is interrupt driven and uses the Output Compare hardware in the 68HC11. Due to the mechanical structure of the platform, the motor is restricted to 160 degrees of rotation.

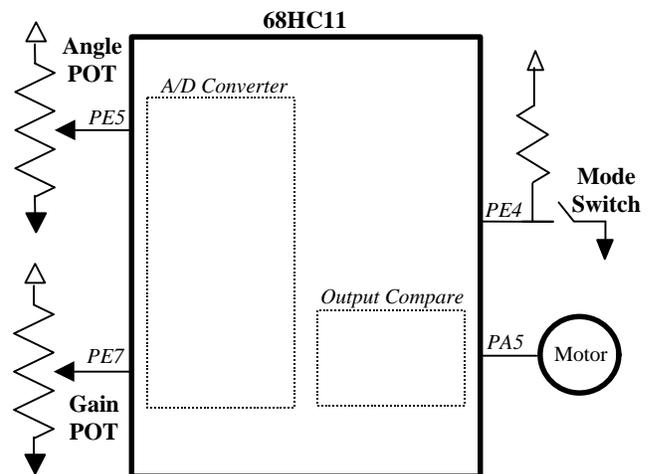


Figure 11: Electronics Diagram

SWING OPERATION

The torque output of the servomotor is directly proportional to the magnitude of the difference between the current and desired positions. The user input at the Gain Potentiometer scales this torque value accordingly. The software for this application commands the motor to a higher torque based on the amount of deflection from the resting position of the swing. The direction that this torque is applied depends on the mode of operation.

SwingBOT has two modes of operation. In the first mode, the deflection-based torque is applied to counteract inherent stiffness. This applied torque, coupled with the driving forces of the

system dynamics, increases the amplitude of the swing oscillations.

At maximum gain, the swing can achieve an amplitude of about 30 degrees from the resting position.

In the second mode, the deflection-based torque is applied in the opposite direction. The stiffness is increased and therefore the oscillation amplitude is reduced. This results in a system that controls the crossbar to maintain the resting position.

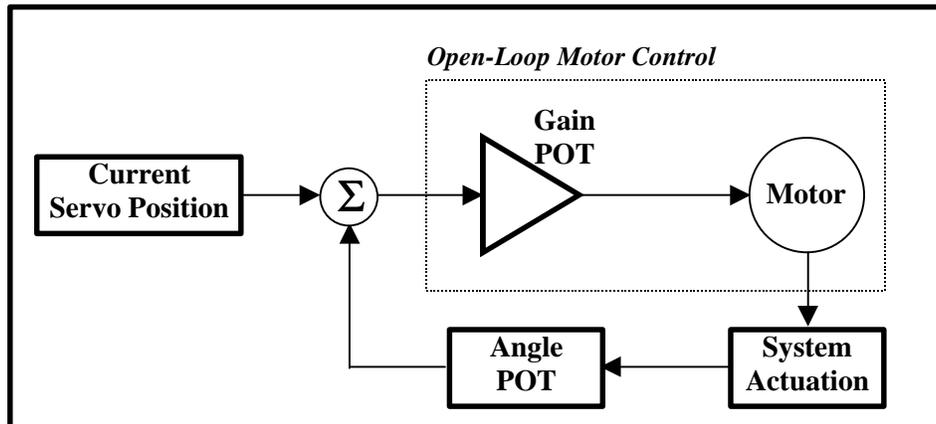


Figure 12: Closed-Loop System Control

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- [2] Serway, Raymond A. *Physics for Scientists and Engineers*. Saunders College Publishing 1990.