Design and Hybrid Control of a Two Wheeled Robotic Platform

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Abstract

As the level of human interaction with robotic systems increases, robot mobility becomes more important. Two wheeled robots offer higher levels of mobility and manoeuvrability when compared to their four wheeled counterparts with the ability to turn on the spot and easily negotiate tight corners. Whilst the stabilisation of two wheeled platforms has been well studied, there is no published research on alternative actuation methods. This study proposes the implementation of a reaction wheel actuator to balance a two wheeled platform within small angular deviations from its equilibrium position. It is proposed that the use of a reaction wheel to deliver the balancing torque instead of the platform drive wheels will lower energy consumption of the system. This hypothesis was derived from the idea that there are fewer energy losses in delivering the torque from the reaction wheel in comparison to the platform wheels. After the design and construction of the platform, standardised tests were carried out to make energy consumption comparisons between the reaction wheel actuated (hybrid) system and the traditional baseline system. The results from these experiments showed that the hybrid system consumed approximately 21% less energy than the baseline system and therefore proves the feasibility of adding a reaction wheel actuator to the system.

***Index Terms* ---- Reaction wheel, robotics, state-space control, linear quadratic regulator, energy efficient balancing.**

I. Introduction

As robotic systems become more mobile and human-like, the physical demands put on these systems also increase. Actions that humans take for granted such as traversing steep hills can be challenging and sometimes impossible for four wheeled systems. These systems become unstable on high inclines due to their centre of gravity no longer existing in a stable region.

Two wheeled systems solve this problem by always positioning their centre of mass such that it always lies above the wheel/ground contact point. These systems have in the past decade become more prominent with small scale designs such as Joe and nBot (Figure 1 a, b) being constructed and published [1, 2].

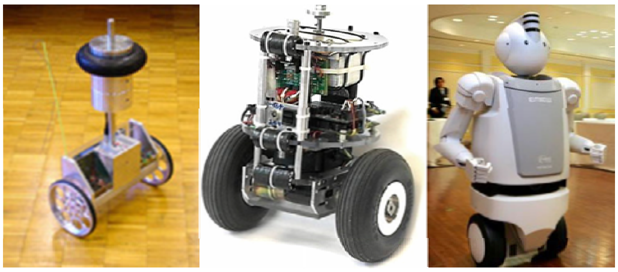

Figure 1a) Joe, b) nBot, c) EMIEW

Small platforms such as these have fast dynamics making their settling times inherently short. Analysis of the robotic platform 'Joe' submitted under '*JOE: A Mobile, Inverted Pendulum*' [1] shows estimated settling times of 2 seconds (Figure 2) to an impulse disturbance which caused the robot to tilt a maximum of 18^0.

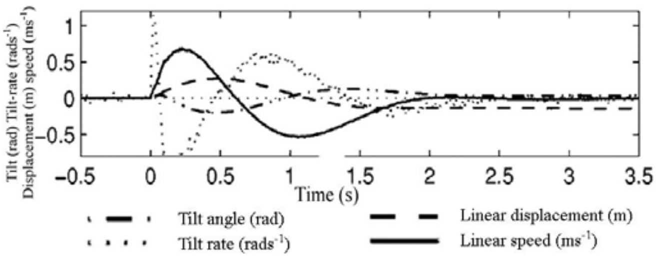

Figure 2 Impulse Response of Joe (adapted from [1])

The method used to test disturbance rejection involved a fixed mass being dropped onto the system at a fixed height. In the case of Joe the corresponding maximum possible energy imparted to the robot in this manner was 1.2 J. This method provides a physical impulse disturbance to the system. This same method was used to test the performance of the platform constructed for our study. The results of these disturbance tests can be seen in the results section of this paper.

In larger systems the increased mass can change the inertial properties of the platform, raising the centre of mass of the system. As the centre of mass of the platform is raised higher, the poles of the open loop system become slower. When making small angle approximations for an inverted pendulum this can be confirmed by equation 1.

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{L}} \tag{1}$$

Where *f=pendulum/natural frequency*
g=acceleration due to gravity
L=distance of centre of mass from wheel axel

In effect whilst the system is slower and hence controlled easier, there is a trade-off with control effort as the overall system is heavier and requires higher levels of balancing torque.

Recent advances in these systems have seen the development of highly advanced robots such as Hitachi`s EMIEW (Figure 1 c) which has been implemented as a hotel clerk. Two wheeled systems such as these allow stability of a naturally unstable system through two actuators (one mounted on each wheel).

These systems have the limitation of only being effective when excellent traction between the tyres and the ground is present. This limitation also means that these systems have issues when momentarily in mid air such as when travelling over bumpy terrain.

Investigation into alternative energy efficient actuation methods for two wheeled robotic platforms has driven this research project into investigating the feasibility of implementing a single reaction wheel as a secondary actuator for a two wheeled inverted pendulum.

Reaction wheel actuators themselves have primarily been used in satellite attitude control and small-scale fixed-base inverted pendulum systems. Reaction wheel systems present unique advantages over traditional drive wheel methods. These include its ability to supply torque while not having contact with the ground. This means that this system could potentially allow the system to travel on low friction surfaces and still maintain stability.

This study fills an apparent gap in research into the feasibility of implementing such an actuator on a two wheeled platform in terms of control stability and energy consumption. As this is a novel concept the scope of this research is aimed towards initial feasibility and hence only the stationary performance of the system was investigated. Advanced features such as turning or low friction stability are outside the scope of this study.

II. Hardware Design

Figure 3 shows the hardware that was designed and built for this research project. The total system (known as the hybrid system) consists of two individual subsystems: the baseline system and the reaction wheel system.

Baseline System

The baseline system involves the drive wheels, the gear train, the two brushless DC (BLDC) motors that actuate the drive wheels and the associated circuitry.

Reaction Wheel System

This system involves the reaction wheel, its drive motor and supporting hardware.

When designing the hardware for this system four principles were considered: safety, functionality, robustness, and modular design. By constructing the system in easy to manage hardware modules, it was possible to rapidly solve problems as the project progressed. Although integrated designs save space, they take a lot more time to implement and reduce design flexibility which is generally undesirable for prototypes.

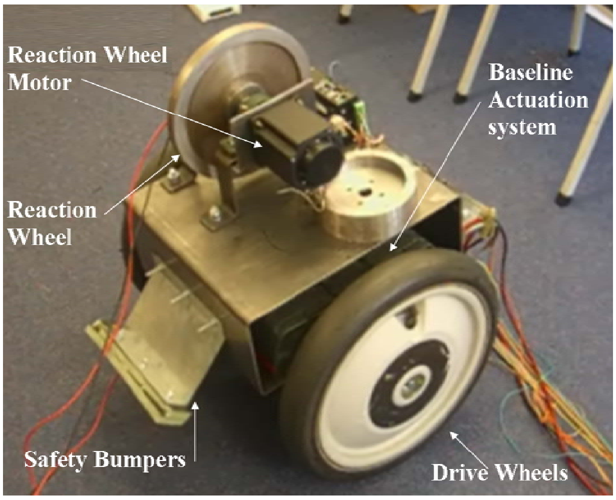

Figure 3 The Final System Used for Testing

The following circuitry was developed by our team:

Analogue to Digital Converter (ADC)

The analogue waveforms sent out of the baseline motors hall sensors were converted into digital pulses. A hysterisis band was introduced to minimize noise effects during switching.

A potentiometer was used to manually tune this band to a desired level. Although hysterisis bands improved noise immunity, they come as a trade off to phase delay. It was observed that the motors benefited from a small amount of phase shift. These hysterisis bands were tuned on each motor to provide equal response in both directions (clockwise/anti-clockwise).

Power Distribution Board

The system's power is drawn from 4 batteries. Each battery cluster contains 24 NiMH cells in series meaning that each of the four battery clusters is a 3 Amp-hour 28.8V nominal voltage. The solution for controlling the safe activation of our system was to use four relays. These electronic switches allowed a method of isolating the user operated power switch from the high voltages and currents involved in this system. Furthermore user operated switches which carry high currents generally have additional circuitry (fuses) and are more expensive.

Signal Distribution Board

In order to communicate with the various sensors and actuators employed in the hybrid system a large amount of wiring was used. Rather than having dozens of tethered wires protruding from the system, a signal distribution board was developed to provide an easy access point for obtaining desired signals. It also allowed for the development of a structured method of data acquisition and reduced the risk of stray wires shorting circuitry.

Additional safety features which proved to be extremely useful during the testing phase were the safety bumpers which protected both the user and hardware from damage.

III. System Modelling

Before proceeding onto designing a controller, the two wheeled robotic platform with and without the reaction wheel actuator was modelled mathematically. There are four key states in the baseline system: linear displacement of the platform (x), linear speed ($\dot{x}$), angular displacement (θ) and angular speed ($\dot{\theta}$) as shown in Figure 4. The controlled input variable in the baseline system is the torque supplied by the drive wheel motor (T_m). When the reaction wheel actuator is added to the system, an extra state is introduced. This state is rotational speed of the reaction wheel (ω). In addition there are two control variables: T_m and the torque supplied by the reaction wheel, T_R. The final non-linear equations of motion which describe the dynamics of the two wheeled platform are given in equations 2 and 3. These equations were derived from [4] and adapted to fit our system

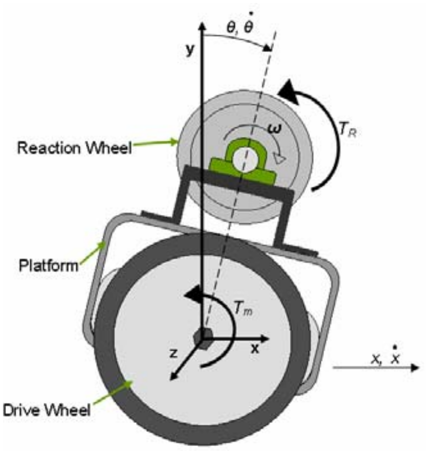

Figure 4: Schematic Diagram of Two Wheeled Platform with the Reaction Wheel Actuator

Baseline System:

$$\ddot{\theta} = \frac{-\dot{\theta}^2\alpha^2\sin\theta\cos\theta + \alpha m_o g\sin\theta - T_m\left(m_o + \frac{\alpha}{r}\cos\theta\right)}{I_o m_o - \alpha^2\cos^2\theta}$$

$$\ddot{x} = \frac{\dot{\theta}^2\alpha I_o\sin\theta - \alpha^2 g\sin\theta\cos\theta - T_m\left(\frac{I_o}{r} + \alpha\cos\theta\right)}{I_o m_o - \alpha^2\cos^2\theta} \tag{2}$$

Hybrid System:

$$\ddot{\theta} = \frac{\alpha m_o g\sin\theta - T_m\left(m_o + \frac{\alpha}{r}\cos\theta\right) - T_r m_o - \alpha^2\dot{\theta}^2\sin\theta\cos\theta}{I_o m_o - \alpha^2\cos^2\theta}$$

$$\ddot{x} = \frac{\dot{\theta}^2\alpha I_o\sin\theta - \alpha^2 g\sin\theta\cos\theta + T_m\left(\frac{I_o}{r} + \alpha\cos\theta\right) + T_r\alpha\cos\theta}{I_o m_o - \alpha^2\cos^2\theta} \tag{3}$$

The motors were also modelled to obtain a relationship between input voltage and output torque as shown in equation 4.

$$T_{motor} = \frac{\frac{3}{2}k_t\left(V_{ph} - k_e\omega\right)}{Ls + R} \tag{4}$$

In order to use an LQR controller the system plant has to be linearised about its equilibrium point, which in the case of the inverted pendulum is the upright position ($\theta = 0^o$). Hence the system is only valid in the region of operation about this equilibrium point.

Feedback of the platform displacement x is not required for balancing and therefore this state is removed from the model.

The mathematical equations for the plant are then linearised about the equilibrium point. This linearization is done using a Taylor series expansion in MATLAB. The resulting state space representations for the baseline system and for the hybrid system are given in equations 5 and 6 respectively.

$$\underline{\dot{\mathbf{x}}} = \begin{bmatrix} 0 & -0.876 & 0 \\ 0 & 0 & 1 \\ 0 & 5.118 & 0 \end{bmatrix}\begin{bmatrix} \dot{x} \\ \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 3.081 \\ 0 \\ -2.895 \end{bmatrix}\begin{bmatrix} V_{DW} \end{bmatrix}$$
$$\underline{\mathbf{y}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \dot{x} \\ \theta \\ \dot{\theta} \end{bmatrix} \tag{5}$$

$$\underline{\dot{\mathbf{x}}} = \begin{bmatrix} 0 & -0.876 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 5.118 & 0 & -0.005 \\ 0 & 0 & 0 & -1.665 \end{bmatrix}\begin{bmatrix} \dot{x} \\ \theta \\ \dot{\theta} \\ \omega \end{bmatrix} + \begin{bmatrix} 3.081 & 2.006 \\ 0 & 0 \\ -2.895 & 0.037 \\ 0 & 13.071 \end{bmatrix}\begin{bmatrix} V_{DW} & V_{RW} \end{bmatrix}$$
$$\underline{\mathbf{y}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \dot{x} \\ \theta \\ \dot{\theta} \\ \omega \end{bmatrix} \tag{6}$$

The two control inputs in these models are V_{DW} and V_{RW} which represent the reference voltage signal to the drive wheel and reaction wheel motors respectively.

IV. State Measurements

Our state measurement system consists of an infrared range sensor, gyroscope and servo processed current and velocity outputs.

The Sharp GP2D120 infra-red sensor was used to determine the tilt (θ) of our system. By using the geometry of the platform (Figure 5), a relationship between the tilt angle and range measurement was derived (equation 7). This sensor was calibrated before installation and fine tuned after mounting.

$$\theta = \tan^{-1}\left(\frac{x_o - x}{y}\right) \quad (7)$$

where

x	*=distance measured by Infra-red sensor (m)*
x_o	*=offset distance (infra-red distance at 0^o) (m)*
y	*= co-planar distance from wheel axle to infra-red sensor emitter. (m)*

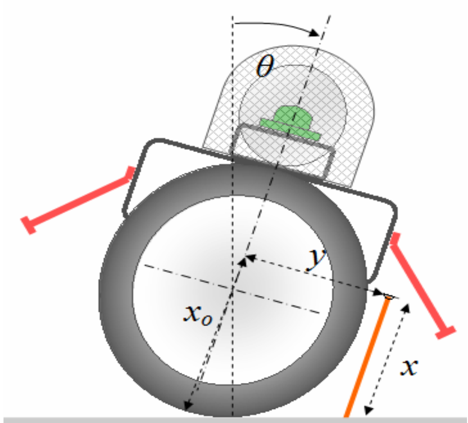

Figure 5: Method for Calculating Tilt Angle.

The ADX300EB gyro was used to measure the change in tilt $\dot{\theta}$ and since this signal was noisy it needed to be low-pass filtered to remove high frequency noise. Drift effects were seen to be minimal.

The wheel speed $\dot{x}$ was obtained from a supplied output of the servo amplifiers. This signal is proportional to the frequency of the hall sensors mounted within the drive-wheel motors. Similarly the reaction wheel speed ω is found.

Current draw by actuators was measured from the servo motor output pins. We also know that power is the rate of energy consumption hence the integral of the power will give us the total energy consumed.

$$E = V\int_{Ti}^{Tf} I(t)\,dt \quad (8)$$

Where

I(t)	*=Current draw from batteries (A)*
Tf	*=Final Time (s)*
Ti	*=Initial Time (s)*
E	*=Energy consumption (J)*
V	*=Constant voltage of battery (28.8V)*

V. Controller Design

Two methods that are commonly used in classic linear controller design are pole placement and optimal linear quadratic regulator (LQR) both of which have been applied to the inverted pendulum. These two methods have frequently been compared in terms of controller performance. The results of these comparative studies have led to a common conclusion; that LQR controllers produce better results in terms of system stability and repeatability [5, 6]. For this reason an LQR controller was selected for this project.

Optimal control systems are designed by minimising a performance index to find the ideal feedback gains for a particular system plant. An LQR compensator allows a trade-off between the control effort applied by the actuators and the amount of regulation for each system state. The performance index in this case is given by equation 9 [7].

$$J = \int_0^\infty \left(\underline{\mathbf{x}}^T \mathbf{Q}\underline{\mathbf{x}} + \mathbf{R}\mathrm{u}^2\right)dt \quad (9)$$

The **Q** matrix contains the weightings assigned to each of the system states and therefore determines the importance of each state over the others. The states with proportionally higher weightings have a larger amount of regulation. The **R** matrix contains the weighting for actuator effort and in this case will determine how much effort is demanded from the reaction wheel motor compared to the drive wheel motors to balance the platform. The complete LQR controller design was carried out in MATLAB. The block diagram of the controller is shown in Figure 6.

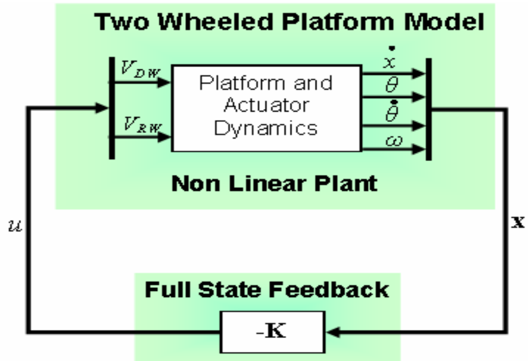

Figure 6: Block Diagram of Control Loop

Baseline Control Strategy

The first control strategy designed (baseline controller) is based on the traditional method of stabilising two wheeled robots. The baseline controller only makes use of the robots drive wheels to provide the control effort to balance the platform. The platform is driven forward and backwards in response to the direction in which it is tilting. This is done to maintain the centre of gravity of the system directly above the wheel axis. For this control strategy there is only one controlled variable which is the voltage signal sent to the drive wheel motors.

Hybrid Control Strategy

The second control strategy designed to balance the two wheeled platform makes use of both the reaction wheel and drive wheel actuators to provide the balancing torque needed. The reaction wheel supplies a balancing torque directly through voltage control of its motor. The hybrid control strategy implemented on this system varies the ratio of control effort from each of the actuators depending on the angle of tilt of the platform. This function is shown in Figure 7 and was designed such that for small angular displacements, between $\pm 4^o$ the balancing torque is delivered almost exclusively from the reaction wheel actuator. After this and until $\pm 5^o$ the torque demanded from the reaction wheel levels off till zero to provide a smooth transition between the two controllers. Outside this range the torque required to balance the system is larger than what the reaction wheel is capable of supplying and therefore the drive wheel actuators take over. It is important for there to be a smooth transition between the use of the reaction wheel and the use of the drive wheels rather than a sudden switching point.

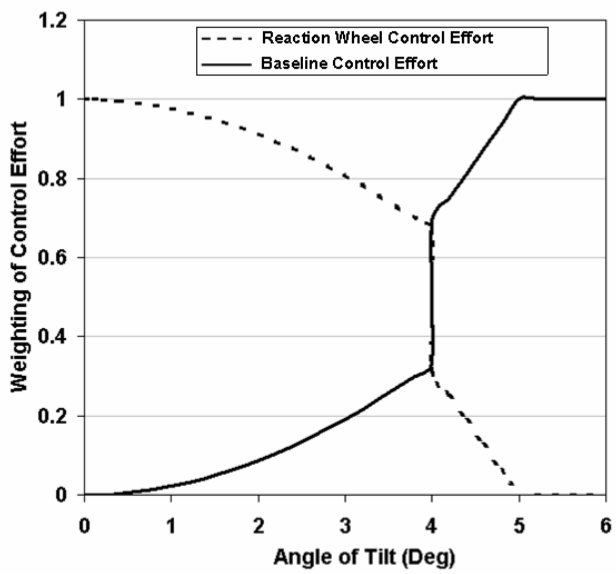

Figure 7: Weighting of Reaction Wheel and Drive Wheel Control Effort Based on Angle of Tilt

The weighting function of Figure 7 was determined experimentally by tuning the performance of the hybrid controller on the two wheeled platform.

VI. Simulation Results

Before implementing the control strategies on the hardware their performance was compared in simulation. The main distinction between the hybrid controller and the baseline controller lies within small angular displacements from the upright equilibrium where the reaction wheel controller dominates the balancing effort. Figure 8 shows the two wheeled platform's response to an initial angular displacement of 4^o under both the hybrid and baseline control strategies.

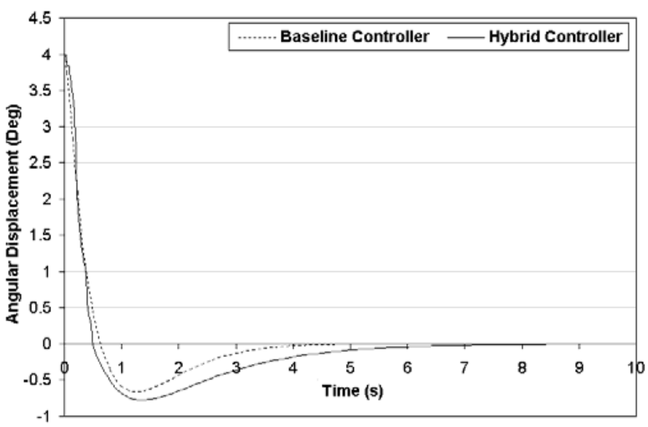

Figure 8: Simulated Time Response of the Platform under the Hybrid and Baseline Control Strategies to a 4^o Initial Angular Displacement

The hybrid controller and the baseline controller show very similar performance for controlling tilt in terms of both overshoot and settling time. For both control strategies, the overshoot in angle is smaller than 1^o. The settling time for angular displacement under the two control strategies are also very similar: 4 seconds under the baseline strategy and 5 seconds under the hybrid strategy. The simulations show that there are no oscillations in angular displacement for either controller. Hence we can conclude that in simulation the use of a reaction wheel to provide the torque needed to balance the platform instead of the drive wheels does not compromise the performance of the system in terms of driving the platform's angle of tilt to zero.

The two control strategies were also compared in terms of energy consumption in Simulink. The energy consumed by each controller to balance the platform from an initial angular 4^o is calculated over a time period of 50 seconds from the time of the disturbance.

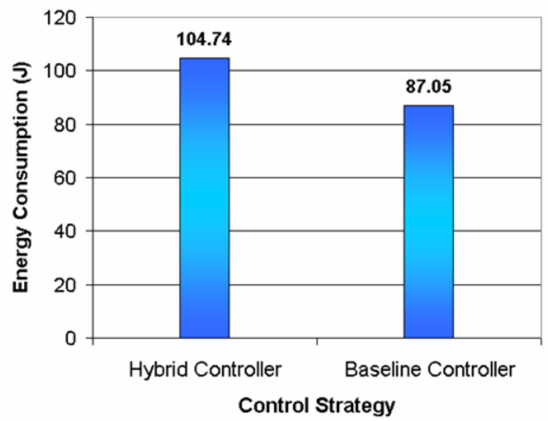

Figure 9: Simulated Energy Consumption by the two Control Strategies

The results in Figure 9 interpret as the hybrid controller using 20.33% more energy than the baseline control strategy to balance the system from the same angular displacement.

However, these are only simulated results and the model used in these simulations is by no means a perfect representation of the real two wheeled platform. It does not take into account non-linearities such as friction and backlash in the drive wheel gear trains, both which will lead to an under estimate for the amount of energy used by the baseline controller.

VII. Experimental Results

The two control strategies are to be compared in terms of response to disturbances, robustness and energy consumption. In order to achieve these objectives, two standardised disturbance tests were created and implemented on both systems.

Stationary Response of Two Wheeled Platform

Before subjecting the platform to any disturbances its stationary response under each of the two control strategies were compared, as shown in Figure 10. It is important to analyse the steady state behaviour of the platform as this is the state the two wheeled robot will be in whenever it is stationary.

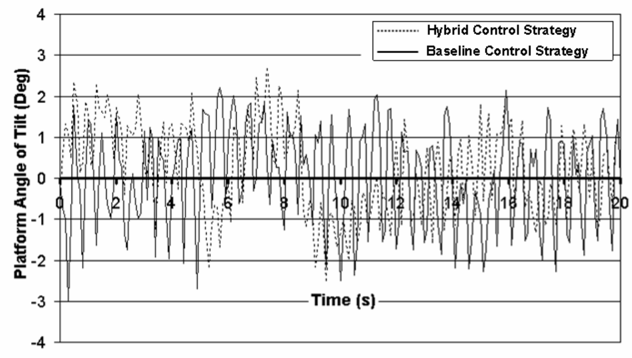

Figure 10: Graphs Showing Level of Oscillation for Tilt Angle for Baseline and Hybrid Control Strategies

Under both control strategies the platform angle of tilt oscillates between $\pm 2^{o}$. This means that in the case of the hybrid controller the balancing effort is coming exclusively from the reaction wheel actuator. From the graph it can be seen that the oscillations in platform tilt angle are much larger and of a higher frequency for the baseline controller than for the hybrid controller.

The conclusion drawn from the simulation results is confirmed on the two wheeled robot itself. The reaction wheel actuator does not compromise the balancing performance of the robot; in fact, it improves its stability as the oscillations in angle are smaller than those in the baseline system.

The data depicted in Figure 10 shows quite a large frequency of oscillation for platform angle of tilt under both the control strategies. Part of the fluctuations in angle measurements is attributed to the infra-red sensor being used to measure this state. Therefore, for the remaining results, the angle data will be filtered using a 3 sample moving average before being plotted or analysed.

Response to Disturbances

The first standard disturbance applied to the two wheeled platform was created by dropping a 204g mass onto a marked target on the back edge (negative angle) of the platform. This was done after the controller was turned on and from a height of 1.325m, hence imparting 2.65 J of energy to the platform, assuming no losses. The response of the platform to this disturbance under both control strategies is shown in Figure 11.

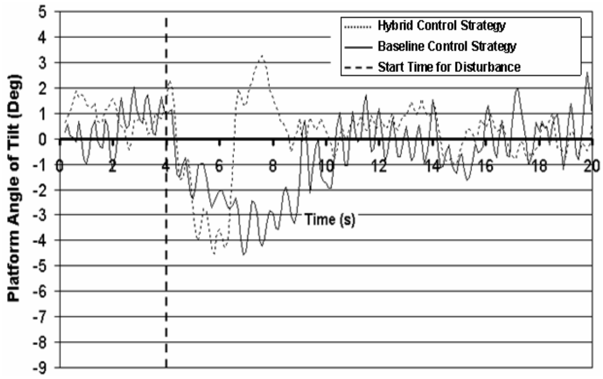

Figure 11: Transient Response of the Angle of Tilt of the Platform, under Each Control Strategy, to a Small Disturbance

The response of the baseline controller to this disturbance is much slower and therefore shows less overshoot than the response from the hybrid controller. This is probably because the drive wheels have to overcome more friction than the reaction wheel does before being able to apply enough correcting action to the platform. The magnitude and frequency of oscillations in angle seen with the baseline control strategy are much larger than those produced from the hybrid control strategy. Overall both systems can cope with this small disturbance with a settling time of about 5 seconds from the time of the disturbance but the hybrid controller shows a more stable and less erratic response.

To demonstrate the robustness of the hybrid controller the same small disturbance was applied to the front of the platform rather than the back. The results from this test showed a similar response to that shown in Figure 11 and prove that the controller is robust to disturbances regardless of the point of application.

Response to the Large Disturbance

For the large disturbance the same mass is dropped from a larger height of 1.785m (3.57J) onto the two wheeled platform.

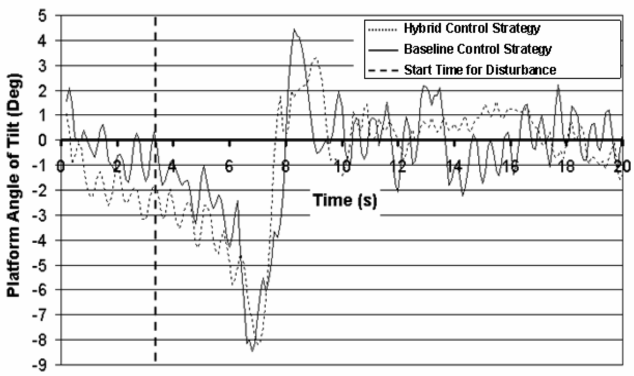

Figure 12: Response of the Two Wheeled Platform to a Large Disturbance under the Baseline Control Strategy

Although the baseline strategy does respond to this large disturbance the oscillations in angle remain slightly larger than they were for the stationary response for some time after the disturbance has been applied. This can be seen in Figure 12 where even 10 seconds after the disturbance has been applied (at around 12-17 seconds) the fluctuations in angle of tilt are between $\pm 3^{o}$. These are larger than the fluctuations seen in the ambient situation. On the other hand, the oscillations in angle for the system controlled by the hybrid strategy are much more contained and do not exceed $\pm 2^{o}$. It's response to a large disturbance once again confirms the robustness of the hybrid control strategy.

Energy Consumption Comparison

The energy consumed by each control strategy to balance the two wheeled platform after being subjected to each of the disturbances is measured using the same methodology used when analysing the simulation results. The time over which the current drawn from each actuator is integrated must be held constant for all tests across both the control strategies. This time period was set as 20 seconds long and begun when the disturbance was applied to the system. In order to increase the accuracy of these results each disturbance experiment was repeated 5 times and the results on energy used were averaged to give the final results shown in Figure 13.

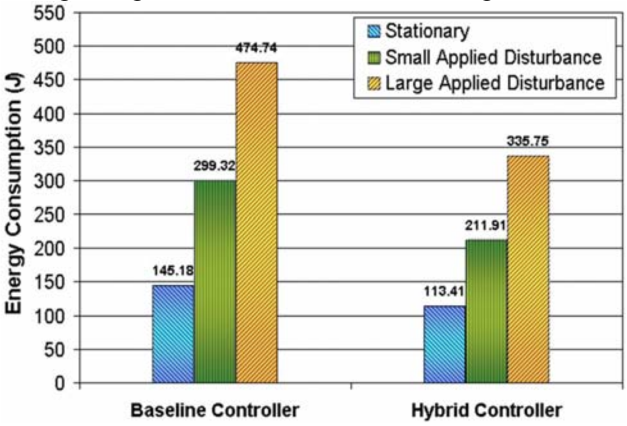

Figure 13: Comparison of Energy Consumed by Actuators under Each Control Strategy for Each Situation

The results from the energy comparison are summarised in Table 1.

Table 1: Summary Table of Energy Comparisons between Hybrid and Baseline Control Strategies

	Baseline (J)	Hybrid (J)	% Difference (Hybrid - Baseline)
Stationary	145.18	113.41	21.88
Small Disturbance	299.32	211.91	29.2
Large Disturbance	474.74	335.75	29.28

Contrary to what was concluded from the simulations, the hybrid control is at least 21% more energy efficient than the baseline controller for all the three situations tested. The hybrid control strategy significantly reduces the control effort from the drive wheels within the angular range of $\pm 4^{o}$. Since the angle of tilt of the platform lies within this range for a majority of its operation this saving in energy from the hybrid controller was expected as the reaction wheel system does not have as many losses as the drive wheel system does. The hybrid controller can therefore supply the platform with the same amount of balancing torque as the drive wheels can without having to overcome friction or backlash.

VIII. Conclusions

Two control strategies were designed to balance a two wheeled robotic platform. The hybrid control strategy makes use of an addition reaction wheel actuator to provide a balancing torque to the platform. The two control strategies were compared in terms of the platform's response to disturbances and the amount of energy consumed by the actuators to achieve balance. The simulation results for the platform response to a small disturbance show that the two control strategies have similar performance in terms of settling time and overshoot for the angle. In terms of the energy consumed by the actuators, the baseline was seen to be more efficient in simulation.

However this did not follow in practice, the experiments carried out on the two wheeled platform showed the hybrid control strategy to be more energy efficient than the baseline control strategy by at least 21% for when the platform was stationary and when it was subjected to disturbances. This is explained by the fact that losses through friction and backlash in the drive wheel gear train were not accounted for in the simulation The performance of the hybrid controller was also determined to be slightly better in that the oscillations in platform angle were of a smaller magnitude and lower frequency than those observed with the baseline control strategy.

Hence we can conclude that the reaction wheel actuator is a feasible addition to aid the balancing of a two wheeled platform both in terms of balancing performance and energy efficiency while stationary and moving in a straight line.

Further research should be undertaken to explore ways to increase its currently limited effective angular range and to determine further benefits from this actuator such as balancing the platform on slippery or uneven terrain. Another recommendation would be to replace the infra-red range sensor with an accelerometer and gyroscope fused inertial measurement unit (IMU) to provide more accurate readings of angle of tilt.

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