Design and Fabrication of I-Cycle

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***Abstract*—This paper proposes a new concept in the electric vehicle in the area of the renewable energy. An I-Cycle is a self-balancing electric unicycle. Although a regular unicycle is pedal-powered and is balanced by the skill of the rider, the I-Cycle is powered by an electric motor and uses a control system to balance in the roll direction. I-Cycle is intended to be a fast and portable means of transportation between public transport, home and office. Further-more, with a learning time of thirty minutes, the I-Cycle brings unicycling to the balance-challenged.**

***Index Terms*—renewable energy, self-balancing, portable, unicycling, centre of gravity (COG), gesture control, PD controller**

I. Introduction

Over the past twenty years, the unicycle has been the subject of a diverse range of papers. Many of these studies have been on a theoretical or educational basis and have not involved building a test device. Additionally, most tend to focus on emulating autonomous (unmanned) unicycles rather than producing a ride able device, which is the aim of the I-Cycle project.

There was limited evaluative literature available on these designs, so a critical design review was performed for the focus designs self-balancing unicycle (SBU) [1], Trevor Blackwell's Electric Unicycle [2] and the Enicycle [3]. It is noteworthy that literature discussing the dynamics of a 'ballbot' is used extensively through this review. A ballbot is a self-balancing robot which stabilises itself in two orthogonal planes on a ball. The dynamics of the ballbot are relevant because the assumption can be made that motion in the two planes of the device are decoupled. Hence the dynamics for each of these planes are applicable to the planar motion of the I-Cycle.

The project aims at the design and construction of a self-balancing unicycle, known as the I-Cycle. A Self-balancing Unicycle is similar to a regular unicycle, but rather than being controlled by the rider's feet on the pedals; sensors, microcontroller and a motor are used to maintain stability in the direction of travel. Roll stability is controlled by the rider through steering with the foot-pegs. The rider can control the speed of travel by leaning forwards or backwards. In this sense, a Self-balancing Unicycle could also be described as a one-wheeled Segue.

The finished I-Cycle has met all the core project goals. The mechanical hardware was resilient throughout the development process and only minor replacements to exterior protective padding were required. The iterative electrical and software development process coupled with the monitoring of issues through the Failure Modes and Effective Analysis (FMEA) resulted in a final device which has a high degree of reliability, predictability and safety. I-Cycle has attracted a significant level of community and media attention, including exhibitions and feature stories in print media, television and radio. Thus in addition to successful development of a self-balancing unicycle for urban use, the project has also established the I-Cycle as an outstanding educative device.

The scope of this project is to design a ride able unicycle, primarily for transport. Therefore, the term 'self-balancing unicycle' is used to refer to a ride able unicycle in which roll stability is provided by a control system. This scope has led to a focus on four core values: practicality, user safety, marketability, and education. The idea of a practical unicycle, let alone a practical self-balancing unicycle, is often met with incredulity. In the public imagination, unicycles are comical devices employed by clowns with juggling balls, and unicyclists regularly endure such witty comments as, "lost a wheel, mate?" [4]. This may well be an example of 'tall poppy syndrome', as a unicycle is inherently difficult to learn and thus people find it easier to ridicule the idea.

A unicycle, especially considered in light of today's commuter transport requirements, is in fact a practical device. Compared with a bicycle, it is lighter, more portable and considerably cheaper. Thus, a unicycle can easily be transported in car boots, trams, trains, and even in lifts to office cubicles. However, with the difficulty of pitch balancing removed, a self-balancing unicycle is no more difficult to ride than a bicycle, yet maintains many of the benefits associated with a regular unicycle. The addition of electric power means that increased distances can be travelled with relative ease. Furthermore, a self-balancing unicycle also improves on other self-balancing scooters by offering better portability, lower cost, and a heightened sense of freedom.

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II. Design and Implementation

The development process includes an investigation of existing designs which are then ranked with a decision matrix. Following this is a discussion of the mechanical design of components that were manufactured for the I-Cycle. These include the fork and spindle assembly, the main chassis, and the seat pole location. The design process focused on achieving five key goals: ease of manufacture, optimal centre of gravity (CoG), durability, design flexibility and aesthetics. To achieve these goals the design process was an iterative process involving modelling the I-Cycle, CoG analysis and a static structural analysis of the critical components to determine component dimensions and CoG of the I-Cycle inclusive with rider.

A. Fork

The fork design [5] addresses the major issue that is, asymmetrical motor rim combination. The wheel has an offset centre plane which is required to be aligned with the centre plane of the spindle. Failure to realign these planes would result in the tyre being in a plane that is not central to the rider. As such, the fork legs are offset as shown in Fig. 1. The forks also incorporate locations to attach rubber bump stops to the ends of the horizontal section to reduce damage to the I-Cycle in case of collision.

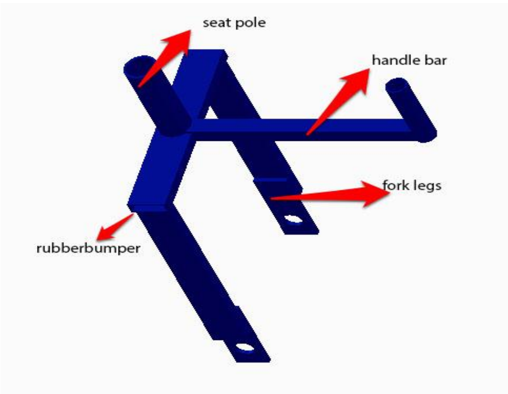

Figure 1. Fork pro-e model

B. Seat Installation and Mass Distribution

The weight bias of the I-Cycle is a critical requirement of the design to allow the I-Cycle to balance in an upright position. To determine the desired CoG, both the I-Cycle and rider's combined CoG were required to be located vertically over the hub motor's axle line to ensure that the balance angle of the I-Cycle was vertical [6]. Pro-Engineer creo 2.0 (ProE) was used in calculating the centre of gravity of the I-Cycle. The connection between the seat and seat post is adjustable in the angular and longitudinal directions as shown in Fig. 2.

C. Combined Chasis Design

The final design, as shown in Fig. 2, incorporates mild steel spacers, rubber bumpers and bash plates as this is the area of the I-Cycle [7] that is affected in the majority of collisions. These extra features are necessary to increase the durability of the design and provide the spacing required for the electrical components. While this is only a prototype design, these measures are necessary to increase the lifetime and functionality of the device

Figure 2. Final I-cycle chases design

III. Electrical Design

A. Sensor Unit

Motion Interface is a must-have function being used in the I-Cycle navigation. With the ability to precisely and accurately track user motions, motion tracking technology can convert user position into data understand by the microcontroller. The MPU-6050 is the integrated 6-axis motion tracking device that combines a 3-axis gyroscope, 3-axis accelerometer, and a digital motion processor (DMP) all in a small 4x4x0.9mm package, as shown in Fig. 3. With its dedicated I2C sensor bus, it directly accepts inputs from an external 3-axis compass to provide a complete 6-axis motion fusion output. The MPU-6050 features three 16-bit analog-to-digital converters (ADCs) for digitizing the Gyroscope outputs and three 16-bit ADCs for digitizing the accelerometer outputs. For precision tracking of both fast and slow motions, the parts feature a user-programmable Gyroscope full-scale range of ±250 to ±2000 °/sec (DPS) and a user-programmable accelerometer full-scale range of ±2g to ±16g.

Figure 3. 6-Axis motion tracking device (MPU 6050)

With all the necessary on-chip processing and sensor components required to support I-Cycle, the MPU-6050 uniquely enables low-power motion Interface with reduced processing requirements for the system processor. Additional features include small package size, low power consumption, high accuracy, repeatability, high shock tolerance, and application specific performance programmability all at a low consumer price point.

B. Control Unit

The control unit is brain of I-Cycle. Arduino Uno along with ATMEGA328, as shown Fig. 4 constitutes to control unit. In order to stabilise the rider in the centre of plain the control unit analyse [8], [9] the data from sensor unit and give signal to the motor driver. The main reason behind choosing this microcontroller is its feasibility to program when in operation and inbuilt debugger.

Figure 4. Arduino uno

C. Motor Driver

In this project an H-bridge made of two TIP147 and two TIP142 as shown in Fig. 5 was used. Based on the signal given by the sensor unit the control unit trigger the transistor Q1 and Q2 for forward direction and Q3 and Q4 for reverse direction of the motor. The proposed driver is capable of driving a motor that runs at 24V and 40Amps.

Figure 5. H-Bridge driver circuit

D. Motor

The designed I-Cycle was capable of driving a load of 120kgs and runs on battery bank. So, to meet the requirements a 300W, 24V brushed DC motor [10] as shown in Fig. 6 was chosen. The reason choosing brushed motor is its high efficiency and easy control.

Figure 6. 300W, 24V brushed DC motor

IV. Implementation

The final I-Cycle product is fabricated by fixing the sensor and control units to the mechanical chases, shown Fig. 7. As explained above, Motion Interface is a must-have function being used in the I-Cycle navigation. With the ability to precisely and accurately track user motions, motion tracking technology can convert user position into data understand by the microcontroller, which analyse the data and gives signal to motor driver which in turn control the motion of the motor there by stabilizes the rider position in the centre plane [11].

Figure 7. Fully fabricated I-cycle

V. System Modelling and Control

In this section, the non-linear dynamics of the I-Cycle system are derived. The assumptions used in this derivation and the definition of terms are both outlined below. Following this, the system dynamics are derived and a relationship between the electrical supply current and the torque produced by the motor is established.

A. Dynamics of the 2 Degree of Freedom (DOF) System

The dynamics of the I-Cycle are developed from the inverted pendulum model used extensively in Driver [12]-[14] to include the translational motion of the pendulum. However, these derivations are inconsistent with regards to coordinate frames and non-conservative forces. Therefore an extensive verification process was based on the dynamics derived in [15], [16] through coordinate transforms, verified with the papers discussed above. The following assumptions have been made in the derivation of the dynamics, with reference to the coordinate system and directions.

- Motion is restricted to xy-plane
- A rigid cylinder is used to model the chassis and a vertically orientated thin solid disk used to model the wheel
- Coulomb friction arising from the bearings and tyre-ground contact is neglected, and hence only viscous friction is considered
- The motor is controlled via an intelligent controller in `current mode' such that the input into the plant is a torque command
- There is no slip between the tyre and the ground
- The model is defined in terms of coordinates φ and θ,

where

φ - Rotation of the frame about the z-axis

θ - Rotation of the wheel relative to the frame angle

The origin of the right-handed coordinate frame is located at the centre of the wheel, as shown in Fig. 8. The positive x-direction is to the right and positive y is upward. The two angular quantities, - and, have been chosen such that anti-clockwise rotations about the z-axis are considered positive. The zero datum for the measurement of the frame angle - is coincident with the positive y-axis and the wheel angle is measured relative to φ.

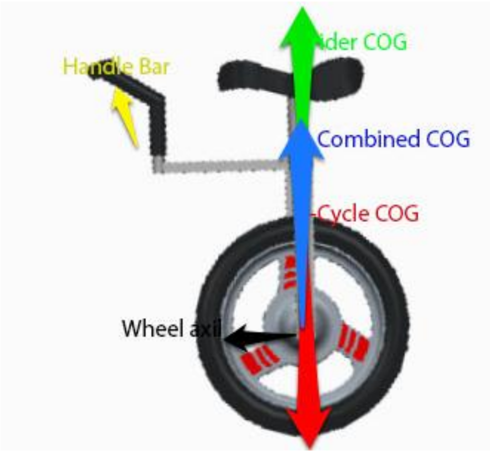

Figure 8. Modelled system for the derivation of the system dynamics

B. Non-Linear Dynamics

The Euler-Lagrange equations, written below, describe the dynamic model in terms of energy and are given by

$$\frac{d}{dx}\left(\frac{\partial L}{\partial q_i}\right) - \frac{\partial L}{\partial q_i} = F_i \tag{1}$$

where, Lagrangian L is the difference in kinetic and potential energies of the system, q_i are the generalized co-ordinates (in this case φ and θ) and F_i are the generalized forces. The kinetic and potential energies of the wheel and frame are denoted K_w, V_w, K_f and V_f respectively

$$K_w = \frac{I_w\dot{\theta}^2}{2} + \frac{m_w(r_w\dot{\theta})^2}{2} \tag{2}$$

$$V_w = 0$$

$$K_f = \frac{m_f}{2}\left(r_w^2\dot{\theta}^2 + r_f\dot{\varphi}\cos\varphi\right)^2 + \frac{I_f}{2}\dot{\theta}^2$$

$$V_f = m_f g r_f \cos\varphi \tag{3}$$

If the generalised coordinates are q= $[\theta \quad \varphi]^T, then$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = \begin{bmatrix}0\\ \tau\end{bmatrix} - D(\dot{q}) \tag{4}$$

where,

$$D(\dot{q}) = \left[\mu_\theta\dot{\theta} \quad \mu_\varphi\dot{\varphi}\right]^T \tag{5}$$

is the vector describing the viscous friction terms. Therefore, the Euler-Lagrange equations

$$M(q)\ddot{q} + C(q,\dot{q}) + G(q) + D(q)^{\cdot} = \begin{bmatrix}0\\ T\end{bmatrix} \tag{6}$$

where the mass matrix, M(q), is

$$\text{M(q)=}\begin{bmatrix} I_w + r_w^2(m_f + m_w) & m_f r_w r_f \cos\varphi \\ m_f r_w r_f \cos\varphi & I_f + r_f^2\cos^2\varphi x \end{bmatrix} \tag{7}$$

of motion can be expressed as the vector of centrifugal effects, $C(\dot{q}, q)$, is

$$C(\dot{q},q) = \begin{bmatrix} -m_f r_w r_f\, \varphi^2 \sin\varphi \\ -m_f r^2{}_f\, \varphi^2 \sin\varphi\cos\varphi \end{bmatrix} \tag{8}$$

And the vector of gravitational forces, G(q), is

$$G(q) = \begin{bmatrix} 0 \\ -m_f r_f\, g\sin\varphi \end{bmatrix} \tag{9}$$

These are described in the standard non-linear state space form by defining the state vector, $x = [q^T \quad \dot{q}^T]$, and the input as u=T. This, together with the above equitation's gives

$$\dot{x} = \left[M(q)^{-1}\left(\begin{bmatrix}0\\ T\end{bmatrix} - C(q,\dot{q}) - G(q) - D(\dot{q})\right)\right] = f(x,u) \tag{10}$$

C. State Estimation

There are two states which the control system [10] is required to measure. These are φ and φ, the angular position and angular rate of the frame respectively. Fig. 9 shows how these states are read from the IMU. Note that the φ value is read directly from the IMU rather than differentiating the φ value. This is because there is less latency in the- filters than the φ filters. However, the filters implemented with the IMU are proprietary. It is known that the φ filters are slower than the φ filters, but no other specifics are known about their structure or frequency response. Thus, the φ was read directly from the IMU rather than differentiating φ.

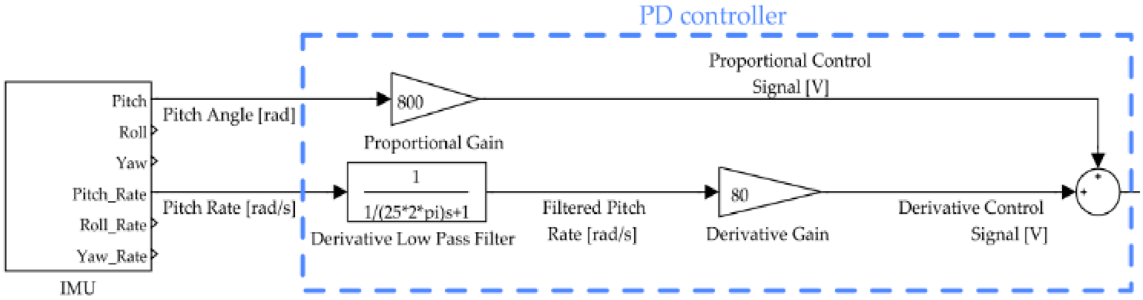

Figure 9. Simulink block diagram representing the state estimation and the PD controller

D. PD Controller

The control strategy employed here uses a standard proportional-derivative (PD) controller. The implementation of this controller can be seen in Fig. 7. The reason for why a PID controller was not used is that a human naturally acts to reduce the steady state error and the addition of integral control can degrade the performance of the controlled response [4]. A low pass filter was used on the derivative control term to make the controller proper and to filter out noise from the sensors in the physical system. The parameters of the tuned control system are presented in Table I and II. The transfer function for the designed PD controller is presented in (1). Note that strictly speaking, the system actually consists of two distinct transfer functions, one for φ and one for φ, as different sensors are used for each state. Nevertheless, this is a PD controller and (1) represents the effective transfer function with the two feedback terms combined.

TABLE I. DESCRIPTION AND VALUES OF VARIOUS SYMBOLS USED IN THE CALCULATIONS

Symbol	Value	Description
r_w	0.203 m	Radius of the wheel
r_f	0.3 m	Distance to the centre of mass of the frame from the origin
m_w	7.0 kg	Mass of the wheel
m_f	15.0 kg	Mass of the frame
I_f	0.45 kgm^2	Moment of inertia of the frame w.r.t. its centre of mass
I_w	0.145 kgm^2	Moment of inertia of the wheel w.r.t. its own centre of mass
$\mu_\emptyset$	0.08 Nm/(rad/s)	Coefficient of rotational viscous friction(bearing friction and motor losses)
μ_θ	0.05 Nm/(rad/s)	Coefficient of translational viscous friction (rolling resistance)
k_r	1.64 Nm/A	Motor torque constant
g	9.81 m/s^2	Gravitational acceleration

TABLE II. DESCRIPTION OF VARIOUS SYMBOLS USED IN THE CALCULATIONS

Symbol	Description
θ	Angular position of the wheel with respect to the frame (anti-clockwise positive)
$\dot{\theta}$	Angular velocity of the wheel
$\ddot{\theta}$	Angular acceleration of the wheel
φ	Angular position of the frame with respect to the positive y-axis
$\dot{\varphi}$	Angular velocity of the frame (anti-clockwise positive)
$\ddot{\varphi}$	Angular acceleration of the frame
τ	Torque applied by the motor, excluding friction
i	Motor supply current

E. Experimental Results of the Closed Loop PD Controller

The above methodology was then applied to the physical I-Cycle, shown in Fig. 7. The results can be seen in Fig. 10 and Fig. 11.

VI. CONCLUSION AND FUTURE WORK

In this paper the dynamics of the unicycle were derived and presented. Future work includes the development of a model based non-linear controller and a back stepping controller. These control strategies will be compared and benchmarked, with the optimal strategy being implemented into the I-Cycle design. A higher capacity motor controller shall also be integrated into the system to alleviate the high tendency to saturate. Another planned development is the addition of active stabilization in the roll direction. This will use either a reaction wheel or a control moment gyroscope and this actuator will allow the I-Cycle to be a completely self-balancing electric unicycle.

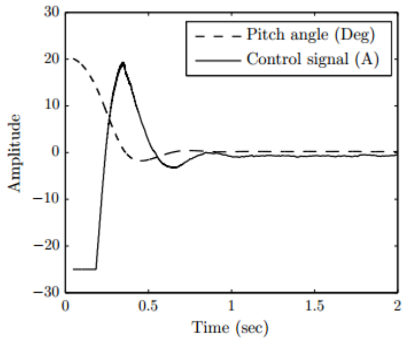

Figure 10. Closed loop response of the constrained physical I-cycle system when rotated to 20 degrees and released.

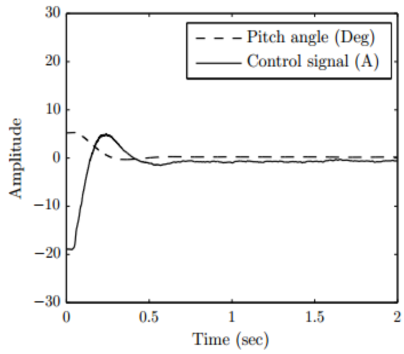

Figure 11. Closed loop response of the constrained physical I-cycle system when rotated to 5 degrees and released

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