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Original scientific paper

DESIGN AND IMPLEMENTATION OF SELF-BALANCING MOTORCYCLE

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A b s t r a c t: In this research paper, an investigation was conducted into the development of mechatronic systems for two-wheeled vehicles, with a primary focus on a self-balancing motorcycle. The self-balancing motorcycle, which is currently in the developmental phase, has a primary objective of enhancing traffic safety by eliminating the requirement for external assistance. The study delves into its design, programming, and potential for further enhancement and eventual commercial utilization. Fundamental equations of bicycle dynamics were derived, and a PID controller, guided by MEMS sensor data, was employed for steering control. The paper encompasses the presentation of experimental tests and refinements to the feedback system, providing valuable insights into the system's overall performance. The research embarks on the intersection of technology, vehicle dynamics, and safety, laying the groundwork for future developments in these interconnected domains.

Key words: self balancing motorcycle; equations of motion; PID control; Matlab Simulink

ДИЗАЈН И ИМПЛЕМЕНТАЦИЈА НА САМОБАЛАНСИРАЧКИ МОТОЦИКЛ

А п с т р а к т: Во овој истражувачки труд е спроведено истражување за развој на мехатронички системи за возила на две тркала, со примарен фокус на самобалансирачки мотоцикл. Мотоциклот со самобалансирање, кој моментално е во фаза на развој, има примарна цел да ја зајакне безбедноста во сообраќајот преку елиминирање на потребата од надворешна помош. Студијата навлегува во неговиот дизајн, програмирање и потенцијал за понатамошно подобрување и евентуално комерцијално искористување. Изведени се равенки на динамиката на мотоциклот, а PID-контролер е употребен за контрола на управувањето. Трудот опфаќа презентација на усовршувања на системот за повратни информации, обезбедувајќи и прикажувајќи добиени резултати во севкупните перформанси на системот. Истражувањето започнува со почетокот на развојот на технологијата, динамиката на возилата и безбедноста.

Клучни зборови: самобалансирачки мотоцикл; равенки на движење; PID-контрола; Matlab Simulink

1. INTRODUCTION

In the rapidly evolving technological landscape the advancements of self-balancing vehicles marks a significant transformation in the field of transportation. As we observe this progression, it becomes increasingly important to delve into the development of smaller, energy-efficient vehicles, specifically focusing on two-wheeled self-driving motorcycles. The authors of [1, 2, 3] have delved into the study of the stability and dynamics of bicycles and how they affect its balance. In [4], a comprehensive review of dynamic modeling for single-track vehicles is presented. Some straightforward second-order dynamic models are introduced in [5] to examine the stability of balance in a bicycle. Conversely, certain researchers have delved into motorcycle dynamics using a multi-body approach [6, 7, 8], which, due to its complexity, is less suitable for control system design.

These compact vehicles offer distinct advantages in terms of space utilization and energy efficiency for individual transportation. To make these vehicles truly practical, the implementation of an effective balancing system is crucial. This research project primarily revolves around the development of a self balancing motorcycle (SBM) controlled by a microcontroller-based PID controller, aimed at enhancing its stability and navigational capabilities. While two-wheeled commercial human vehicles such as SEGWAY, NBot, and JOE have already entered the market, their high-tech, high-quality components have rendered them scarce, costly, and largely inaccessible. In contrast, this research project seeks to build a prototype using off-the-shelf components, thereby reducing costs and increasing accessibility. The scope of this research encompasses the assembly of the SBM robot, its mathematical kinematic modeling, and the design and implementation of an Arduino-based PID controller on the assembled robot. This scientific paper is part of an undergraduate thesis with the topic "Development of a concept of a mechatronic self-balancing motorcycle".

2. DERIVING EQUATIONS OF MOTION FOR A BALANCING MOTORCYCLE

The motorcycle balancing issue can be assumed as an inverted pendulum with an attached inertia wheel. The two primary assumptions are that:

A pendulum rod that is fixed to the ground via a revolute joint, thereby possessing one degree of freedom. For modeling purposes, it is assumed that the pendulum rod takes the form of a cylinder characterized by a radius denoted as 'r' in further equations.

An inertia wheel that is linked to the pendulum rod through an additional revolute joint. Similar to the pendulum rod, the inertia wheel is also represented as a cylinder, with a radius designated as 'R' in further equations. Notably, the axes of rotation for the two considered revolute joints are parallel to each other.

The model of the SBM which will be used in the following equations is represented in Figure 1, where *A* represents the rotation axis of the revolute joint connecting the pendulum rod to the ground and has a length l_{AD}, which corresponds to the length of the motorcycle frame. *B* signifies the center of mass of the pendulum rod. It's important to note that for our modeling purposes, we assume that the pendulum rod possesses a uniform density, which implies that point *B* is positioned at the midpoint between points *A* and *D*. *C* denotes the rotation axis of the revolute joint connecting the pendulum rod to the inertia wheel.

In this paper the system under consideration has two degrees of freedom and its state can be characterized using two coordinates: the angle θ, corresponding to the pendulum rod's lean angle, and the rotational speed of the inertia wheel ω.

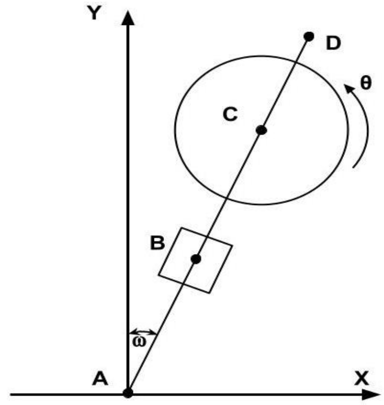

Fig. 1. Scheme of self-balancing motorcycle

The inertia wheel rotates around point *C*. and is in rotational movement about point *A* in conjunction with the pendulum rod. The parallel axis theorem is used in order to calculate the moment of inertia of the inertia wheel concerning point *A*, denoted as I_W^A

$$I_w^A = I_w^C + m_w l_{AC}^2 = 0.5 m_w R^2 + m_w l_{AC}^2 = \\ = m_w(0.5R^2 + l_{AC}^2), \quad (1)$$

where m_w is the mass of the inertia wheel and l_{AC} is the distance between the points *A* and *C*.

The pendulum rod rotates around point *A*, not its center of mass *B*, and its moment of inertia is given by the following equation:

$$I_r^A = I_r^B + m_r l_{AB}^2 = \frac{1}{12} m_r(3r^2 + l_{AD}^2) + m_r l_{AB}^2, \quad (2)$$

where m_r is the mass of the rod and l_{AB} is the distance between points *A* and *B* and l_{AD} is the distance between points *A* and *D*.

The torque τ_m of the inertia wheel is given by the following two equations:

$$\tau_m = I_w^C(\dot{\omega} + \ddot{\theta}) \quad (3)$$

$$\tau_m = 0.5 m_w R^2(\dot{\omega} + \ddot{\theta}) \quad (4)$$

Next step is bringing the above equations of motion to state-space format which is defined as:

$$\dot{x}(t) = (\dot{\theta}\ \ddot{\theta}\ \dot{\omega}) = \\ = \left(\dot{\theta}\ \frac{(\theta)\,(m_r l_{AB} + m_w l_{AC}) - \tau_m}{m_w(0.5R^2 + l_{AC}^2) + \frac{1}{12} m_r(3r^2 + l_{AD}^2) + m_r l_{AB}^2}\ \frac{\tau_m}{I_w^C} - \dot{\theta}\right) \quad (5)$$

Finally this equation is used in the software to model the dynamic behavior of the system and in designing the feedback controller

3. BLOCK-BASED MODELING OF THE MOTORCYCLE MOTION

The programming the motorcycle's motion is done through the use of block-based modeling. The modeling process is organized in design phases with a specific objective, ultimately leading to the attainment of the Final Code. In the initial phase of programming within Matlab Simulink, the emphasis is on parameter configuration to facilitate the creation of a simulation model for the motorcycle's motion. Additionally, an algorithm is devised to maintain the vehicle's balance under varying external conditions. Within this phase, a proportional-derivative (PD) controller is implemented to determine the motorcycle's lean angle and its rate of change over time. These parameters are leveraged to construct a Simulink model aimed at regulating the flywheel's speed, thereby contributing to the motorcycle's balance. To achieve this a Simulation Data Inspector (SID) shown in Figure 2 is implemented.

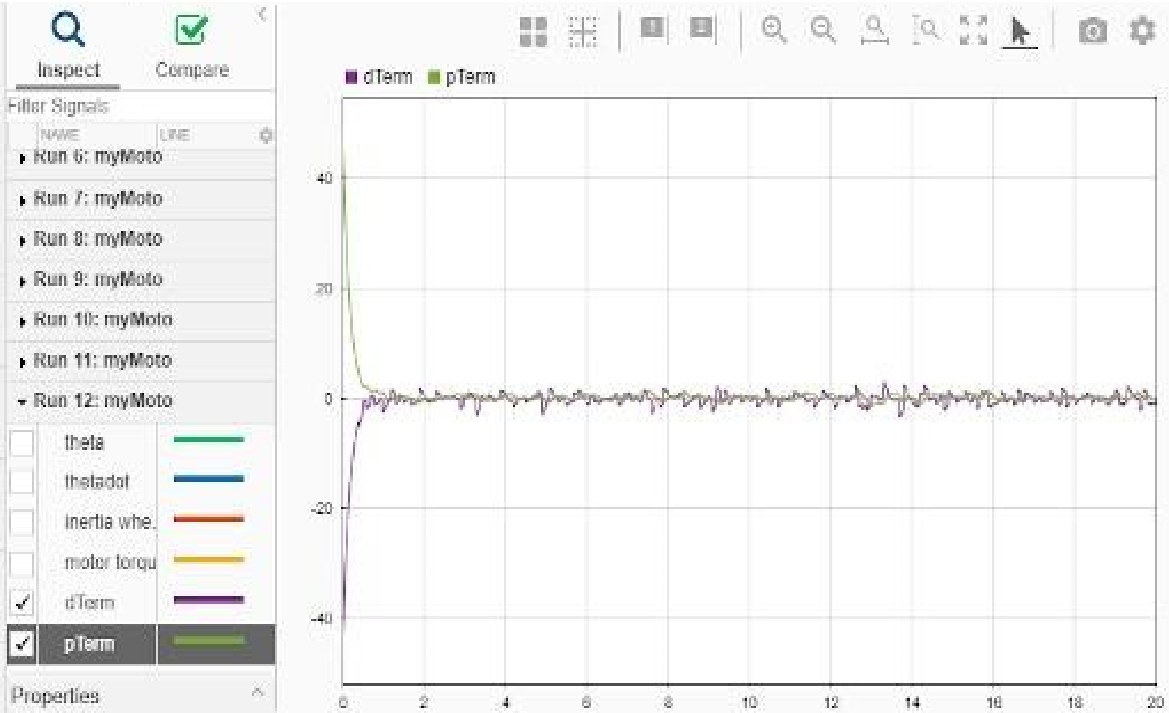

Fig. 2. Control terms in the Simulation Data Inspector (SDI)

The second phase focuses on developing Simulink models to govern the motorcycle's hardware components. Custom algorithms are introduced, enabling direct deployment to the controller from Simulink and the necessary connections with the PD control algorithm are established.

Within the next phase a wireless connection is established and the motorcycle is balanced while moving in a straight path, either forward or backward. To accomplish this, a Wi-Fi connection is established between the controller and the computer, allowing remote monitoring of the motorcycle's status and computer signals without physical linkage. The actuation of the motorcycle is through the rear wheel and the balancing is achieved by the flywheel and gyroscope information from the IMU sensor.

The final phase incorporates the control of the steering servo-motor, enabling left and right maneuvers. This phase tests the ability of the control algorithm to maintain balance while the motorcycle undergoes turns. The act of turning introduces an additional torque component along the wheel-ground axis, necessitating compensation by the flywheel. Altering the steering angle prompts the servo motor to swiftly shift the steering column from its initial angle to the target angle.

4. RESULTS AND DISCUSSION

The final results of the undergraduate thesis are the construction and real time control of a self balancing motorcycle using Matlab Simulink. Having modeled the dynamics of the system and derived the equations of motion the final proportional derivative control could be designed and implemented in order to achieve a stable system. The prototype of the self balancing motorcycle can be seen in Figure 3.

The control of the motorcycle is done through a wireless, Wi-Fi, connection between the MKR1000 controller on the motorcycle and Matlab Simulink. This control allows the motorcycle to move independently without the need of being connected to a computer which will hinder its movements and affect its capabilities. The final code that is used in order to control and balance the motorcycle is given in Figure 4.

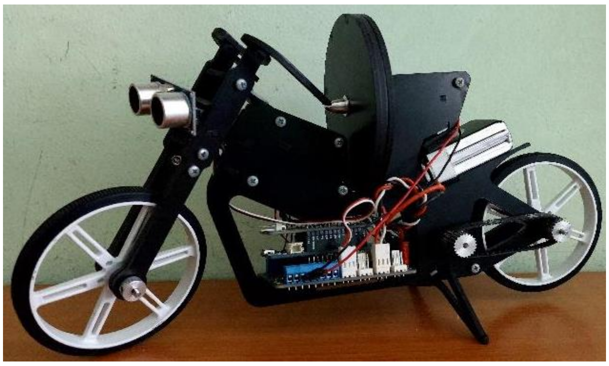

Fig. 3. Prototype of a self-balancing motorcycle

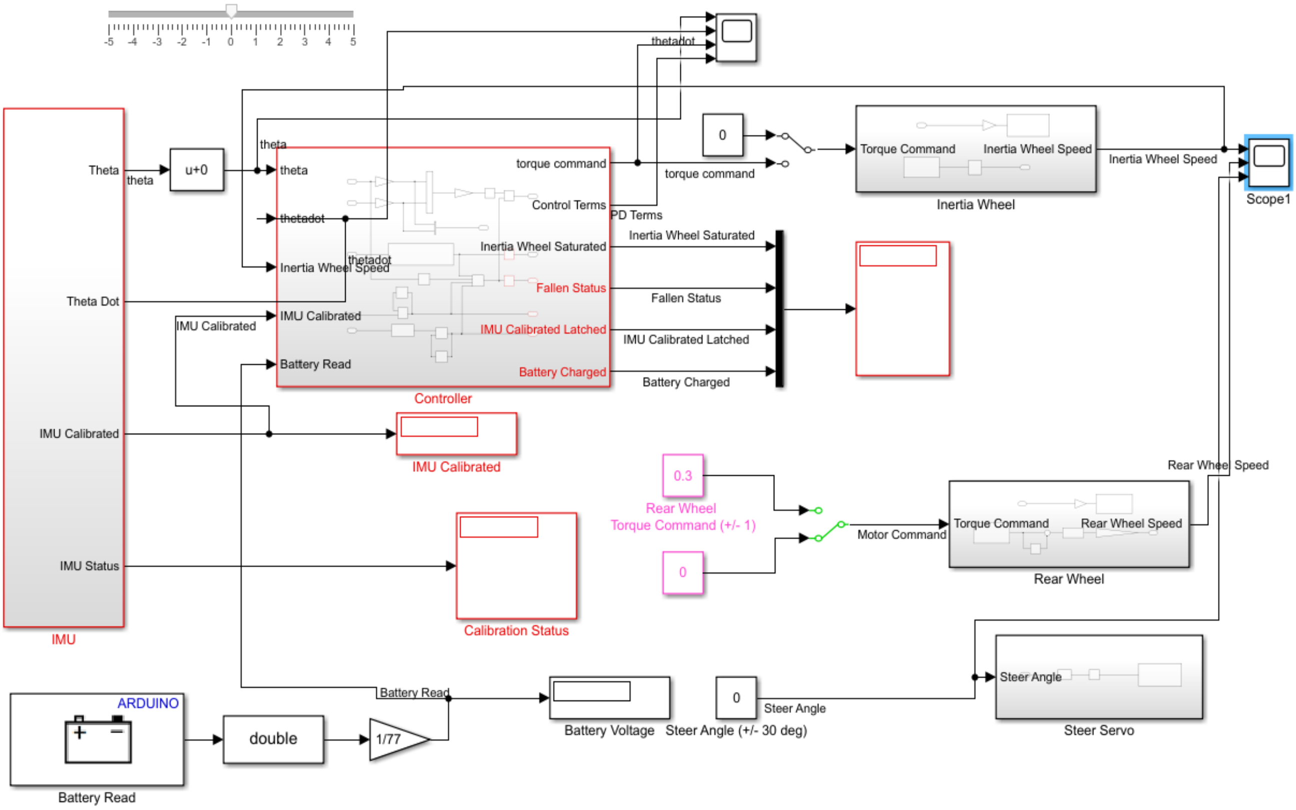

Fig. 4. Schematic of the Final matlab code

The code has multiple aspects which incorporate all of the hardware components on the motorcycle. The IMU sensor gives three-dimensional acceleration, yaw rate and magnetic field strength data in 3 perpendicular axes. This data is used to get the angle and speed at which the motorcycle is leaning in order for the flywheel to stabilize the system. The information from the IMU sensor is fed into the controller which calculates the torque needed for the inertia wheel in order to balance the motorcycle. The PD control is used in order to control the flywheel based on the data from the IMU sensor in order to achieve balance of the motorcycle while the other movements, such as speed of the actuating wheel and the steering are done by user input. The rear wheel speed is commanded as a fractional duty cycle with positive values indicating forward motion and a manual switch is provided to enable or disable the rear wheel motor. While steering of the motorcycle is done by manually inputting the angle at which the motorcycle should turn.

5. CONCLUSION

Within this paper the dynamics of a self balancing motor were presented and its equations of motion have been derived.With the use of Arduino hardware components have been used in the construction of the prototype of the self balancing motorcycle and matlab simulink in its operation. Tuning of the PD controller has been made in order to stabilize the system and ensure it will not fall over while riding. Future work will encompass the addition of extra weight to the motorcycle which will shift position to simulate a rider. Scaling the motorcycle to a bigger version and seeing the hardware needs and costs for such a solution. Finally the work will be done in automating the full system not just the balancing of the motor, this will incorporate automating the steering and the speed of the motorcycle so that they are no longer user input defined but defined based on a task.

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