Robotic platform for position control of a ball

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Abstract. The present paper proposes and describes an approach to stabilizing a ball on a rectangular surface using a three-armed robotic system. The system is based on advanced image detection for accurate ball and surface identification. The hardware includes three servo motors controlled by an Arduino board, and the camera used is a mobile phone connected to the computer. The control of the arm movements is achieved by a PD controller. The components were printed with a 3D printer. The technical details of the system, as well as the PD controller are presented in detail, highlighting the effective interaction between the theoretical and practical sides. The development of this system offers an interdisciplinary perspective, combining knowledge from mechatronics, machine vision, and robotic control.

Keywords: Robotic control, Image processing, Rehabilitation control.

1 Introduction

In recent decades, the field of robotics [1], [2], [3] has seen significant advances, bringing with them new challenges and opportunities in the development of autonomous systems. One of these areas is real-time robotic control [4], where advanced technologies [5] are used to coordinate and regulate the movements of mechanical systems. In this context, the present article proposes an approach for stabilizing a ball in the center of a rectangular surface, using a complex system consisting of three robot arms controlled by servo motors.

The aim is to develop a control system capable of monitoring and adjusting the position of the ball on the given surface. This approach requires the use [6] of a closed control loop in which information from the environment is captured by a video camera.

The system determines the necessary commands for the servo motors of the robot arms, thus keeping the ball in the center of the surface.

Works such as [7], [8], [9], [10] have addressed similar position control problems using different technologies and algorithms. Relevant aspects of machine vision and image processing are discussed in [11]. These previous works serve as reference to our work. The development and implementation of the system in [12] integrates knowledge from mechatronics, control engineering, machine vision, and signal processing [13], [14]. [15] served as inspiration to use small servo motors, and a low-cost development board to implement the described detection and control algorithm. A key issue is the robustness of control systems to disturbances and uncertainties given the dynamic environment and variable interactions with the ball and the surface. Robust control strategies are discussed in [16], motivating the choice of a PD controller. Also, the dynamic model is described as in [17].

The main goal is to present a multidisciplinary educational project with variations in the fields of mechanics, image processing and control. Similar systems have been developed and advanced control approaches used. For example, [9] presents an effective control based on neural networks. In this paper, we show that a simple PD controller can also stabilize the system. Also, such a project is one with low costs, the advantage being given by the development board used and the use of the phone's camera for image detection instead of a specialized camera.

The article presents the hardware design, the mathematical model, control strategies, and software applicability. It is intended as a first step to implement functional software in medical robots, which are currently having a great impact. The designed and developed platform is versatile and can be used effectively in ankle rehabilitation applications, such as [18].

The article is structured as follows: In Section II the hardware part is presented, including the development board, the servo motors and the 3D support; in Section III we describe the image processing and ball detection; Section IV presents the mathematical model of the system and the controllers described; in Section V the results are presented, and Section VI concludes the paper.

2 Hardware design

For the hardware design of the system, we opted to use three servo motors to control the movements of the robotic arms and thus the position of the platform via an Arduino board. This system provides a flexible and efficient platform for implementing control algorithms. We chose SG90 micro servomotors [19] because of their precision and ability to control specific rotation angles. They allow precise adjustment of the angle of rotation, smooth and controlled movements, essential for keeping the ball on the rectangular surface. Parameters such as speed, torque, and angular position can be adjusted using the Arduino board for implementing the controller.

The Arduino Nano board (small, direct connection to computer) is the core of the control system, facilitating efficient communication between the computer and servo motors. Programs implemented on the Arduino receive information from the computer and generate the appropriate signals to control the arm movements. The board also offers the possibility to use a diverse set of software libraries and resources such as Servo and UART serial communication libraries [20], [21], simplifying the development and implementation of control algorithms.

Using a mobile phone as a camera has many advantages. Modern phones are equipped with high-performance cameras and image sensors, providing quality data for visual analysis. This is why we chose to use a mobile phone instead of more advanced camera system.

To design the structural components of the system, 3D modelling of the arms and other necessary elements (like support elements) was first realized. This process allowed an accurate and adaptable design to the geometric requirements of the system. The size of the platform is $140\ x\ 140\ mm$. The elements were subsequently printed using a 3D printer. The PLA materials used for printing are selected for strength, durability, and weight to ensure optimal operation of the robotic arms. The 3D model and the resulting platform are shown in Fig.1. The servo motors are located under the platform and control its inclination through the angle of rotation. The motors are located $61mm$ from the center, every motor rotated with $120\ degrees$. The camera is placed above the board to detect its entire area, including the position of the ball when it is placed. The spherical couplings are at a distance of $65\ mm$ from the center of the platform. The distance of the platform from the table is chosen to ensure the largest and most efficient range of movement of the platform and is $58\ mm$. The arm between A and B is $36mm$ long, between the engine and A the arm is $26\ mm$ long.

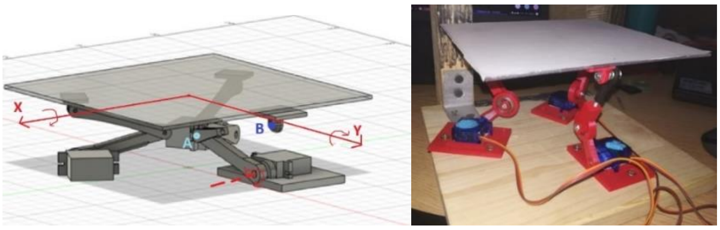

Fig. 1. 3D model and the actual system

3 Image processing

Image detection is a crucial component in our system, and the use of the OpenCV library in the Python language has significantly facilitated this functionality.

For surface identification, we implemented *cv2.findContours* from *OpenCV*, a function that locates and highlights contours in an image. This allowed us to define and delineate the area we consider relevant for keeping the ball in the center of the rectangular surface. The algorithm dynamically adapts to changes in light and contrast, thus ensuring consistent and accurate detection of the area of interest. These image sensing techniques are integral to obtain the position of the ball and platform and to control the position of the ball.

For ball detection, we used the *cv2.HoughCircles* function from *OpenCV*, which is based on the Hough transform [22] to identify circles in images. This algorithm is used for accurately identifying the position of the ball on the platform. The parameters have been tuned based on the actual radius of the ball and experiments to ensure robust detection that is adaptable to operating environment variables. Fig. 2 illustrates how the platform is delineated and how the ball is detected.

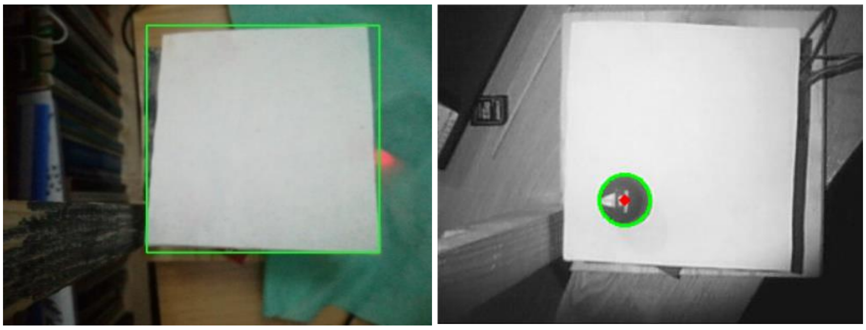

Fig. 2. Platform and ball detection

4 Geometric model calculation

Since the ball on the platform is unstable, precise ball stabilization involves controlling platform movements. To achieve this goal, the servo motors are used to change the platform angle in the x and $y-$axis direction. Therefore the backward kinematics, i.e., the motor angles as a function of the controlled platform angles are computed.

Our system has three actuators (red in Fig. 1 under the white platform), providing three degrees of freedom when positioning the platform. These degrees of freedom are represented by the angles on the x and $y-$axis and the distance of the platform from the table. The kinematic model of the system is based on [23]. The dynamic model [24] is obtained considering the angle r as an input and the position as output. Point A is a rotary coupling, Point B is a spherical coupling. Given the height imposed by the system, we compute the coordinates of points A and B, as shown in Fig. 1, and we obtain a system of equations providing arithmetical connection between the angle of the motors and the $x - y$ angles of the platform.

5 Controller design and results

Under the assumption of two friction and stiction, the dynamic model [17] in the direction of the x-axis is:

$$\ddot{x} = g \cdot sin(u) \tag{1}$$

where $g = 9.81 m/s^2$ and similarly for the y-axis.

To control the system, both PID and PD controllers were considered. The controller provides a desired x, y angle for the platform, which is converted to servo motor angles determined based on the geometric model. Since our goal is to stabilize the ball at a desired position (x^d,y^d). The position error on the x axis is computed as $e_x = x - x^d$ and the desired velocity should be 0. So $e_{vx} = v_x$.

A stabilizing PD control law was determined as:

$$Command_x = e_x \cdot (-0.08) + e_{vx} \cdot (-0.018) \tag{2}$$

where the control gains were tuned to ensure fast error correction, and to reduce overshoot.

A comparison was also made between a PD and a PID regulator. A larger overshoot and a more pronounced oscillation can be observed in the case of the PID regulator, compared to the more calibrated response given by the PD regulator. The x position of the ball using the PD and PID controllers in simulation is shown in Fig.3.

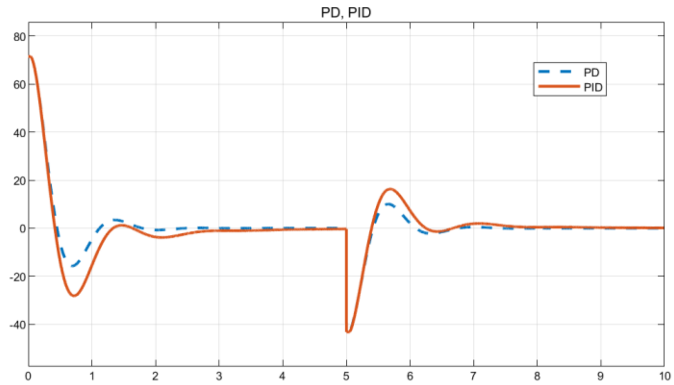

Fig. 3. Simulation results

Although the gains were initially experimentally chosen, the PD control provably stabilizes the ball at a desired point. One can, for instance, use the Lyapunov function:

$$V(e_x, e_{vx}) = 1.5 \cdot {e_x}^2 + 1.9 \cdot {e_{vx}}^2 + 0.15 \cdot e_x \cdot e_{vx} \tag{3}$$

which is positive definite and its derivative along the trajectories of the closed loop system is negative for initial points close enough to the desired point.

Therefore, for practical implementation the PD controller (2) was chosen. The controller was then implemented in Python and loaded on the board to control the servo motors in discrete time, with a sampling period of $Ts = 0.03\ sec$. Implementation on the hardware allowed fine adjustments, such as taking into account a delay that occurs due to the video camera of the phone that captures the image and optimizations in real time.

The experimental results can be seen in Fig.4. We have also tested the disturbance rejection capabilities at second 49 when a disturbance occurs, which is rejected.

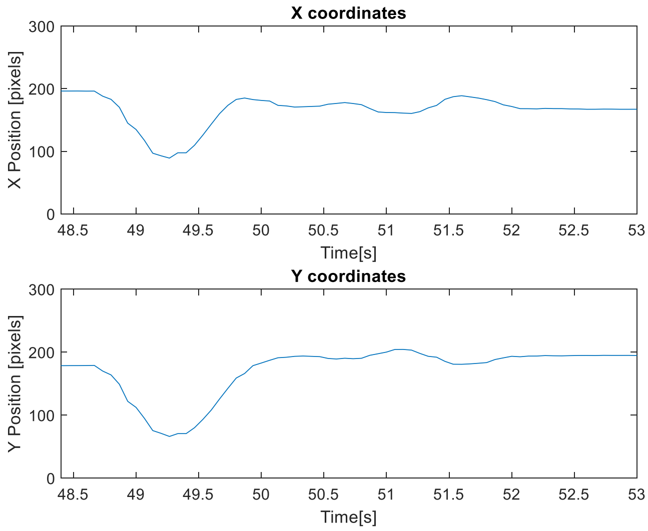

Fig. 4. Experimental results

A video of one of the experiments is available at https://www.lendek.net/files/videos/raad24.mp4

6 Conclusions

This paper describes a solution for stabilizing a ball on a rectangular surface. By using a three-arm servo-driven system with image-based control, the project demonstrates the potential of combining several domains (3D printing, image processing, robot and servo motor control). Stabilization and disturbance rejection was achieved using a PD controller.

Extending this perspective could have significant applications in the field of rehabilitation. Medical robots are used to assist in the medical rehabilitation of patients with different neuromotor deficits, helping to improve mobility and motor function. Similarly to controlling the position of the ball, a PD controller is useful for developing advanced human-robot interactive activities.

By implementing an advanced detection system, without the need for additional markers, the platform allows ball tracking in this initial project. Similar approaches will be developed to detect the position of a limb, either upper or lower, by analyzing its relative movements to the joint in question. The images provide real-time data about the position and movement, thus contributing to the effective assessment and management a rehabilitation process. Several modes of human-machine interactions in which position control is necessary are described in [18]. By implementing a position control algorithm, this platform has the potential to become a useful tool to assist patients in executing correct and controlled movements [25]. The control algorithm is simple enough to be implemented in medical rehabilitation where active human-robot interaction, combined with other multimodal stimulation techniques has shown great potential based on multiple clinical trials with assistive, resistive and path guidance as elective control solutions for chronic patients [17]. A pilot study for this control solution on a lower limb rehabilitation device is scheduled for clinical trials this year.

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