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EXECUTIVE SUMMARY OF THE THESIS

Towards the development of an autonomous guide for visually impaired users for sport activities

LAUREA MAGISTRALE IN AUTOMATION AND CONTROL ENGINEERING - INGEGNERIA DELL'AUTOMAZIONE

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1. Introduction

Visual impairment significantly impacts on daily activities, such as navigating unfamiliar environments, avoiding obstacles, accessing buildings and services, and participating in physical activities. Leveraging technology to address these challenges is crucial for fostering inclusivity and improving the overall quality of life of visually impaired people. In sports, e.g., in running, visually impaired individuals encounter significant challenges in conducting their training sessions independently and necessitate assistance.

To support visually impaired individuals, various devices and aids have been designed and developed. However, most of these devices feature a passive connection between the user and the guide, lack specific design considerations for sports training sessions, and typically function by pulling the user.

This thesis has been conducted in the framework of the BUDD-e project (Blind-assistive aUtonomous Droid Device), whose aim is to develop a robotic guide to assist visually impaired individuals and to create a solution that overcomes current technological limitations and empowers users in diverse environments, including sports. One of the objectives of this thesis is

to design a system that enables active and efficient interaction between the user and the robot. This system must be capable of maintaining a constant force on the user through a tether and handle, irrespectively to variations in the user and robot's speeds. To this purpose, three configurations of the smart tether system have been developed throughout the thesis. Configuration 3, detailed below, features a high-performance motor that significantly enhances the system's capabilities. The earlier configurations, Configurations 1 and 2, are based on the older setup with hardware and algorithmic improvements with respect to the configuration proposed in [3]. These configurations are thoroughly described in the thesis; however, for brevity, they will not be discussed further.

2. BUDD-e and the Smart Tether System

The BUDD-e system, shown in Figure 1, includes two parts:

- a self-balancing robotic platform (Yape)
- a Smart Tether System, comprising a winch connected to a tether and a handle.

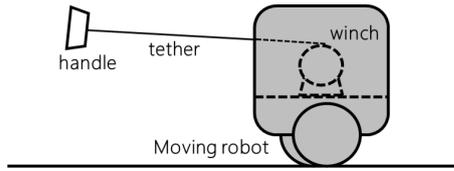


Figure 1: Budd-e components scheme

Yape (see Figure 2) is a differential drive mobile robot with a two-wheeled inverted pendulum structure whose role is navigating and avoiding obstacles and adapting to the user's velocity by perceiving his/her position.



Figure 2: Yape

The Smart Tether System [2] serves as a physical link between the robot and the user. Its primary objective is to maintain a consistent force on the user through the handle, the non-elastic rope, and the elastic tether (see Figure 3), thereby conveying directional motion information.

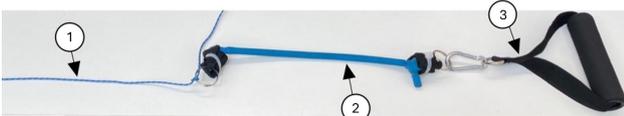


Figure 3: The Smart Tether: 1. Non-elastic cable; 2. Elastic cable; 3. Handle.

The Smart Tether System is integrated into the inner compartment of Yape. It comprises various components, illustrated in Figure 4.

The high-performance motor can be directly controlled in torque and it is suitable for high-speed operations, which is essential for handling dynamic sports activities.

Control is managed by the Nanotec controller (N5-2-2). A load cell is used for force monitoring, while the NME2 absolute encoder ensures precise position tracking and motor control. The winch, connected to the motor shaft, is used to coil a rigid rope.

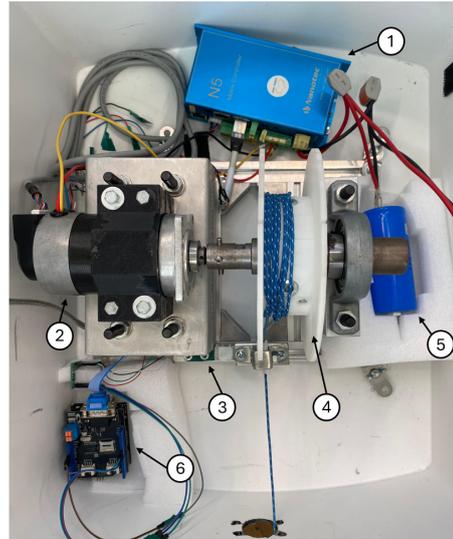


Figure 4: The Smart Tether System: 1. N5-2-2 controller; 2. Motor; 3. Load cell; 4. Winch; 5. Capacitor; 6. Arduino board.

Control and communication are managed by an Arduino board and CAN-BUS Shield, implementing the CAN protocol for efficient data transmission.

The motor control system employs a closed-loop method known as sine commutation via an encoder with field-oriented control (FOC).

Torque control ensures the motor handles the interaction with the user with a controlled amount of force, releasing the rope when the force exceeds a set torque to maintain constant tension. The system operates in velocity mode: the target speed is set and, during operation, the motor adjusts its speed to match this target value.

Safety functions are integrated into the control system to prevent the user from being pulled too close to the robot or being left too far behind. The motor speed is reduced to zero when the user is too close to the robot, specifically within a distance of 70 cm (position value -2000, individuated by the absolute encoder), as shown in Figure 5. Conversely, if the user is too far away, beyond 170 cm (position value 8000), the torque is increased to 700% of the rated current to pull the user closer (see Figure 6). Additionally, the system features linear speed adjustment; between the distances of 115 cm (position value 1000) and 70 cm, the target speed decreases proportionally until it reaches zero (Figure 5).

These safety measures are crucial for avoiding damage or injuries and ensuring rapid and safe

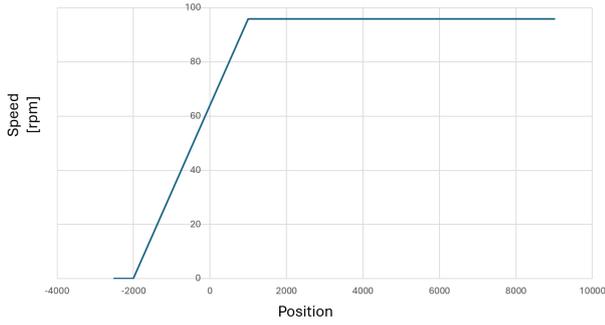


Figure 5: Speed safety functions

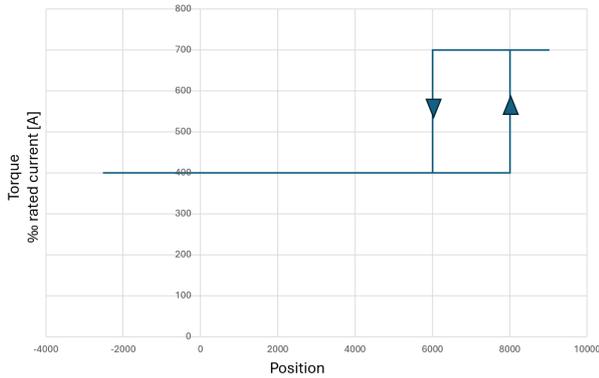


Figure 6: Torque safety functions

responses to the user's movements, being particularly beneficial for visually impaired users engaging in dynamic activities such as sports.

3. Validation of the Smart Tether System

The performance and limitations of the smart tether system have been assessed through an experimental campaign at the Human Performance Lab, Politecnico di Milano - Sede territoriale di Lecco. This setup included a high-speed Technogym treadmill and a table positioned in front of the treadmill (Figure 7) to hold the smart tether system.

Various volunteers tested the smart tether system by moving at speeds 1.5, 4, 6.5, 9, and 12 km/h while holding the smart tether handle. The position of their hand and of the smart tether system was measured with an optoelectronic system. Some illustrative data collected are shown in Figures 8 and 9.

The exerted force was recorded using the smart tether electronic board and compared to the controller's torque recordings converted to force (in gray in Figure 9).



Figure 7: Motor fixed on the table

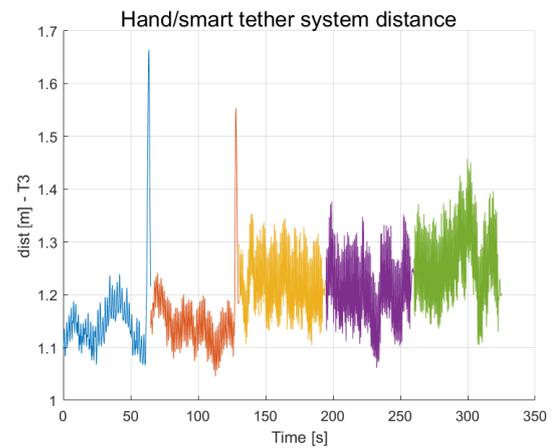


Figure 8: Distance between the hand of tester T3 and the smart tether system. The data refer to $v_{BVI} = 1.5$ km/h (blue), 4km/h (orange), 6.5km/h (yellow), 9km/h (purple), 12km/h (green).

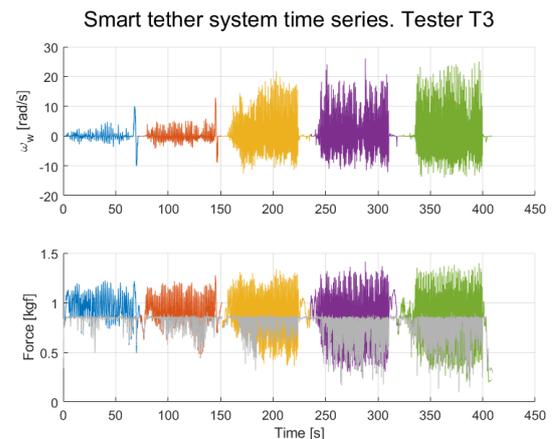


Figure 9: Winch velocity and Force for Tester T3. The data refer to $v_{BVI} = 1.5$ km/h (blue), 4km/h (orange), 6.5km/h (yellow), 9km/h (purple), 12km/h (green). Measurements of the torque provided by the Nanotec controller (gray) [kgf].

The analyzed smart tether configuration has significant responsiveness and reactivity. The motor allows for significantly precise force control even at elevated speeds. In fact, the winch velocity could reach -10 rad/s when coiling the cable and up to 40 rad/s when releasing it, compared to the -2 and 2 rad/s limits in the previous configurations. The force exerted on the user was kept within a limited and acceptable range ($F_{BVI} \leq 1.4$ kgf) even at the maximum treadmill speed of 12 km/h.

The force exerted on the user and the distance between the hand and the smart tether (see Figure 10) have been analyzed in frequency domain.

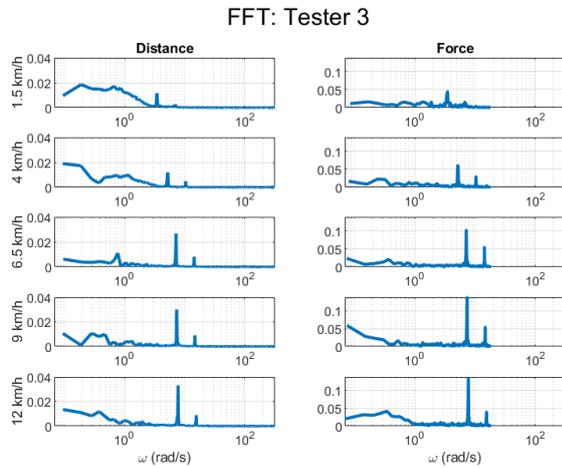


Figure 10: Fourier transforms of hand-table distance (left) and of F_{BVI} (right) for different treadmill velocities (from the top to the bottom) $v_{BVI} = 1.5$ km/h, 4 km/h, 6.5 km/h, 9 km/h, 12 km/h.

Due to the efficiency and responsiveness of the motor, at all tested speeds, this configuration showed significant attenuation of frequency components.

4. Distance control

BUDD-e is schematically represented in Figure 11, where p_{BVI} is the position of the user, v_{BVI} the velocity of the user, p the position of Yape, d the distance between Yape and the user, v the velocity of Yape, v_{ref} the reference velocity of Yape, and F_{BVI} the force exerted on the user by the Smart Tether System. One of the main features of BUDD-e is its ability to adapt to the user speed to maintain a constant, safe and optimal reference distance with respect to

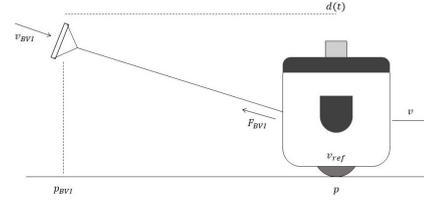


Figure 11: BUDD-e scheme.

the user. The distance control system utilizes LiDAR technology for precise distance measurements and user velocity estimations. A distance control system is designed for this purpose (see Figure 12). The control law aims to make the robot's speed v adapt to the user's speed v_{BVI} and maintain the desired distance d_0 .

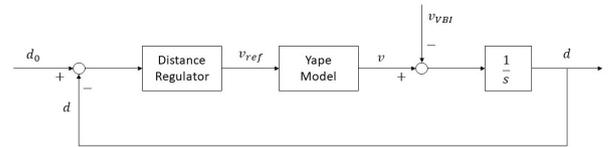


Figure 12: Yape distance control scheme.

The identification of the Yape dynamics was done starting from some experiments in [4] and different behaviors of Yape in acceleration and deceleration were highlighted. Two different transfer functions, i.e. (1) and (2), are identified, for acceleration and deceleration modes respectively.

$$F_{acc}(s) = \frac{1 - 0.3423s}{1 + 2.3728s + 0.9681s^2} \quad (1)$$

$$F_{dec}(s) = \frac{1 - 0.4255s}{1 + 0.6187s + 0.2059s^2} \quad (2)$$

For the distance control of the BUDD-e dynamics, we derive a time-invariant control law using LMI arguments, robust against the specific mode of operation and the transitions between them. A discrete-time state-space realization of the system model is derived and illustrated in detail in Chapter 6 of the thesis. Discretizing this model with sampling time $T_s = 0.1$ s, we obtain the switching system

$$\mathbf{x}_{k+1} = A_i \mathbf{x}_k + B_i u_k \quad (3)$$

where $i = acc, dec$. For controller design, we apply to the switching system (3) an \mathcal{H}_2 norm minimization approach [1]. The application of this

approach is detailed in Chapter 6 of the thesis. Moreover, the distance controller integrates an integral action with anti-windup to address uncertainties in user speed estimation and enhance robustness.

Experimental validation (See Chapter 6.4 of the thesis) of the controller shows promising results, with the system responding smoothly to changes in the reference distance and user speed. The tests demonstrate quick achievement of steady-state conditions and validate the controller's ability to maintain the desired distance under varying user speeds. However, challenges remain in scenarios with abrupt changes in user speed, highlighting the need for further refinement in handling sudden stops, see Section 5.

5. Distance controller in braking conditions

To ensure that Yape swiftly and accurately responds to user braking actions, we propose the following approach.

- Braking Recognition: through multivariate analysis on smart tether data, we can reliably and promptly identify the user brake.
- Feedforward Braking is proposed to minimize reaction time, ensuring the robot stops almost simultaneously with the user. This strategy enhances both safety and comfort.

In order to perform the multivariate analysis, data were collected during tests where the user stopped multiple times while walking or running on the athletics track at Giuriati Sports Center. During these tests, before the stops the robot speed was set and maintained constant. The variables analysed are F_{BVI} and $\tilde{\omega}_w = \max(0, \omega_w)$ where ω_w is the angular velocity of the smart tether system. Data were separated into two sets: a normal set, used for training, and a braking set. From the training set, we computed the covariance matrix at each velocity, which is then used to compute the weighted mean \bar{S} of S over the velocities. Using the covariance matrix \bar{S} , we compute the Mahalanobis distance to determine the statistical distance of new measurements $x(k)$ from the training set:

$$T^2(k) = x(k)^T \bar{S}^{-1} x(k) \quad (4)$$

Given a significance level α , the ellipsoidal con-

fidence region is defined by:

$$T^2 \leq T_\alpha^2 = \frac{(m)(n-1)}{(n-m)} F_\alpha(m, n-m) \quad (5)$$

where $F_\alpha(m, n-m)$ is the upper $100\alpha\%$ of the F distribution with m and $n-m$ degrees of freedom. The system is in braking condition if $T^2(k) > T_\alpha^2$ and it is in normal condition otherwise.

The results of the tests are analyzed in terms of threshold exceedance count and detection delays as shown in Figure 13.

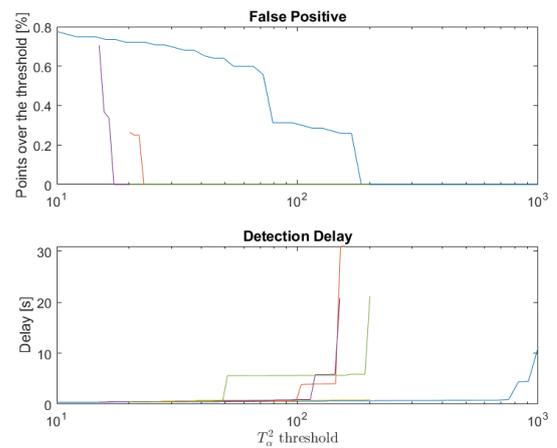


Figure 13: Braking detection performed with variable $\tilde{\omega}_w$ at different velocities: in blue 1 m/s, in red 1.5 m/s, in yellow 2 m/s, in purple 2.5 m/s and in green 3 m/s.

The choice of the most suitable option for the threshold T , for each velocity, requires a compromise between threshold exceedance count and time delay. The metric used to determine the best threshold value is the normalized Euclidean distance D_{norm} between the origin and the points from the graph, as shown below:

$$D_{norm} = \sqrt{\left(\frac{TD}{TD_{max}}\right)^2 + \left(\frac{TEC}{TEC_{max}}\right)^2} \quad (6)$$

where TD represents the time delay and TEC represents the threshold exceedance count. Braking detection based solely on $\tilde{\omega}_w$ showed low threshold exceedance counts and acceptable detection delays, making it the preferred method. For the online implementation of the braking detection algorithm, we developed a velocity-dependent threshold. By interpolating optimal thresholds across different delays, we achieved similar detection delays with limited

increases in threshold exceedance counts (Figure 14).

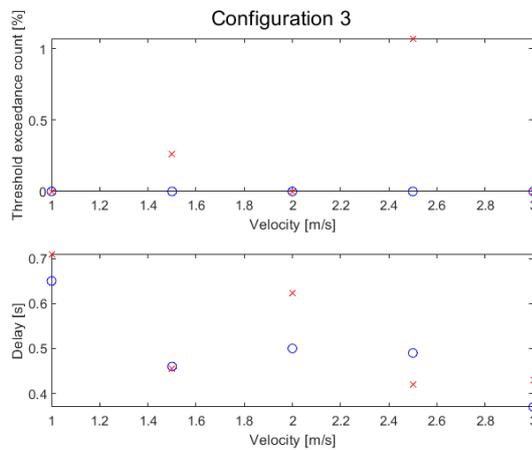


Figure 14: Threshold exceedance count (upper plot), detection delay (lower plot). Blue dots: optimal points; red crosses: points found after the interpolation.

6. Conclusions

The objective of this thesis is to design, implement, and realize a robotic guide for visually impaired individuals, with a particular focus on facilitating engagement in sports activities. This goal is achieved by designing, integrating and controlling the smart tether system and by proposing a strategy for robot speed control even in case of unexpected user brakes. Some experimental campaigns have been conducted to validate the developed control systems.

References

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