A Control Strategy for a Tethered Follower Robot for Pulmonary Rehabilitation

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***Abstract*—Patients that suffer Chronic Obstructive Pulmonary Disease (COPD) underwent a procedure called Pulmonary Rehabilitation that helps them to improve disease prognosis. During Pulmonary Rehabilitation procedures patients require external oxygen assistance. The oxygen tank cannot be carried by the patient and some external assistance is required. In this work a basic robot follower is proposed to carry the oxygen tank based on a differential tethered scheme. Two algorithms are proposed in a very basic configuration.**

***Index Terms*—robotics, tethered, COPD**

I. Introduction

CHRONIC Obstructive Pulmonary Disease (COPD) is an umbrella term that describe several pulmonary affections characterized by a eskeletomuscular atrophy [1], [2]. In order to carve these after effects a Pulmonary Rehabilitation procedure is a viable treatment for these patients. During these procedures patients underwent controlled walking activities and physical exercises under the supervision of a physical therapist. These patients are characterized by a severe low saturation illness and they require effective oxygen supply, particularly when performing physical activity [3]. Hence, patients require to carry with them an oxygen tank for the oxygenotherapy assistance. However, their own condition prevent them with the ability to precisely carry the often bulky external tank. This situation entails a pragmatic solution to provide an additional physical therapist solely for the purpose of carrying the oxygen tank. Alternatively, they require to devise a customized wheelchair to allow them to carry the oxygen tank on top of it, leading to a cumbersome situation for the physical therapist because s/he had to push and maneuver the wheelchair, and at the same time, take care of the patient and perform the rehabilitation treatment.

The scenario may be aggravated by the fact that this procedure is performed on a rehabilitation gym that could be potentially crowded with several patients, physiologist and physical therapists.

An alternative solution is to use an assitive ground service robot [4] to carry the oxygen tank, while following the patient in a leader-follower configuration. There are two reasons that support the initial viability of this idea. First, the rehabilitation gym is a constrained environment where this problem can be tackled by an Unmanned Ground Vehicle (UGV). On the other hand, the range of movements performed by the patient during the Rehabilitation Procedure is highly predictable by the treatment. At the same time, the global robotic research community persuade the development of robotic affordable solutions to the social and health-related worldwide problems [5].

For the implementation of the leader-follower strategy, several solutions have been proposed, including SLAM solutions, vision-based systems or based on electromagnetical beacons [6]. The work presented by [7] explores a differential tethered robotic system to perform camera-based gait analysis of the leader. For COPD Pulmonary Rehabilitaiton procedures, the patient is already umbilicaly linked to the oxygen tank via the breathing cannula. Hence, a robotic solution can exploit this circumstance to perform the *following* mechanism based on a tethered controller. Tethered robots have been extensively researched in robotics [8]. They offer a very simple solution to some common navigation problems, and they can be very effective in robot-to robot interaction, collaborative robotics, or while interacting with humans in Human Robot Interfaces [9], [10], [11].

On the other hand, several assistance devices for COPD treatments have been proposed. Particularly relevant are novel telemedice applications to enhance complementary rehabiliation exersice at home that can track biological markers for those patients [2]. The work presented here follows the line pointed by [12]. Authors studied the use of a single thread tethered follower robot for home oxygen therapy, and compared two different control algorithms and their effectiveness to mimic the leader path and to avoid obstacles. However their approach, focuses on the usage of the device exclusively for home therapy, and not within the context of a Pulmonary Rehabilitation procedure performed by medical personnel on medical installations.

Hence, this work aims to provide an initial study on the controlling mechanism of a differential tethered robot that implements the leader-follower configuration on a Pulmonary Rehabilitation procedure. This document unrolls as follows. Section II describes poses the problem and the solution design, Section III document the experimental protocol to perform the solution assessment on a simulation and on a real world scenario. Results and Discussions are described in IV and V. The Clinical Assessment performed jointly with medical personnel is tackled in Section V-A. Finally, conclusions are exposed in the remaining section V-B.

II. Materials and Methods

In order to prioritize several iterations that could be verified by key stakeholders, we developed a simple robotic prototype

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constructed on Internet of Robotic Things [13]. This discipline is part of what is being called 4th industrial revolution and is reshaping many aspects of global manufacturing, including robotic and healthcare.

A. Solution Design

The medical community is frequently skeptical to technological solutions for medical personel [14], [15], [16], [17]. At the same time, development process as design thinking and other similar tendencies prioritize rapid development, prototyping that can bring quickly feedback from real users about the drawbacks and improving opportunities. In this context, it is important to perform rapid prototyping.

The proposed solution is a tethered robot follower, using a pair of strings. The following mechanism is implemented by means of measuring encoders on two different reels located according to figure 2.

The driving mechanism proposed is a differential wheel robot.

B. Hardware

In order to achieve quick prototyping cycles, we used extensively tools and modules to the IoRT wave. Frames are constructed from aluminum extrusions produced by Makeblock (Shenzhen, China).

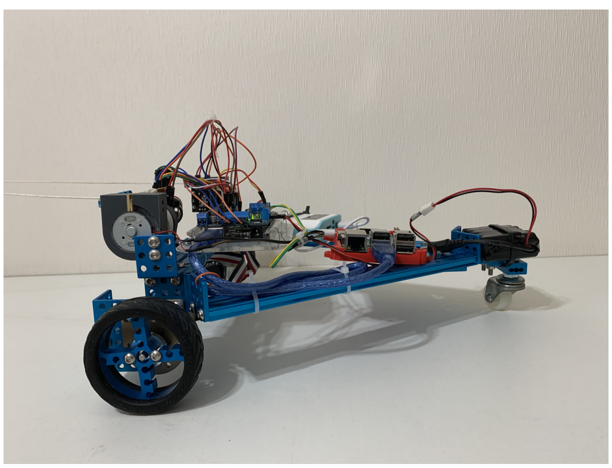


Fig. 1: This robot prototype.

Motors are in-wheel configuration and they provide optical encoding. A microcontroller is used to implement motor controlling and encoder processing. This is based on the popular Arduino platform. On top of it the Adafruit Shield v2. This Arduino bridge can be used to control simultaneously four DC motors.

The microcontroller is connected through serial connection to the main SBC RaspberryPi Model 3B+. The main controlling algorithm run on this board, it connects to wifi and provides telemetry and the abiilty to receive remote commands by means a very simple UDP command interface.

Reels were designed from PVC extrusions based on figure. They are glued to regular DC motors scavenged from old compact discs. Hardware specifications are described on table **??**.

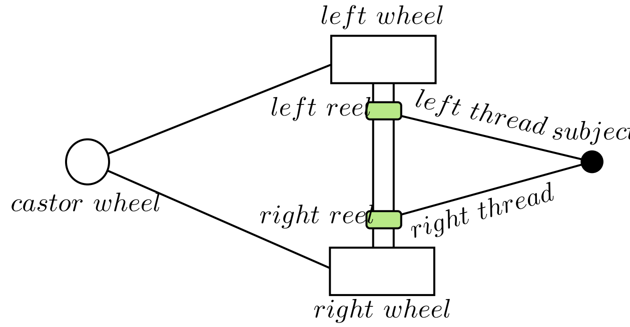


Fig. 2: Components of the robotic vehicle and following mechanism

C. Active Reel Spring

As previously mentioned, an active spring mechanism is also put in place to keep the threads tense at all times and measure the distance to the subject precisely. This active spring mechanism can be implemented by just activating both reel motors at all times to keep the threads tense. However, in order to extend the useful life of the reel motors, and to save battery, an algorithm to intelligently activate and deactivate the motors was developed.

The algorithm works as follows:

1) While wheels are moving, retract reels.
2) If wheels stop moving, wait for *reel wait time* seconds, then retract reels.
3) Retract reels until the reel encoders values have not changed during *reel retract time* seconds.
4) If wheels started moving or the encoder values have changed while retracting, start the *reel retract time* countdown again.

D. Software Components

E. Control Strategy

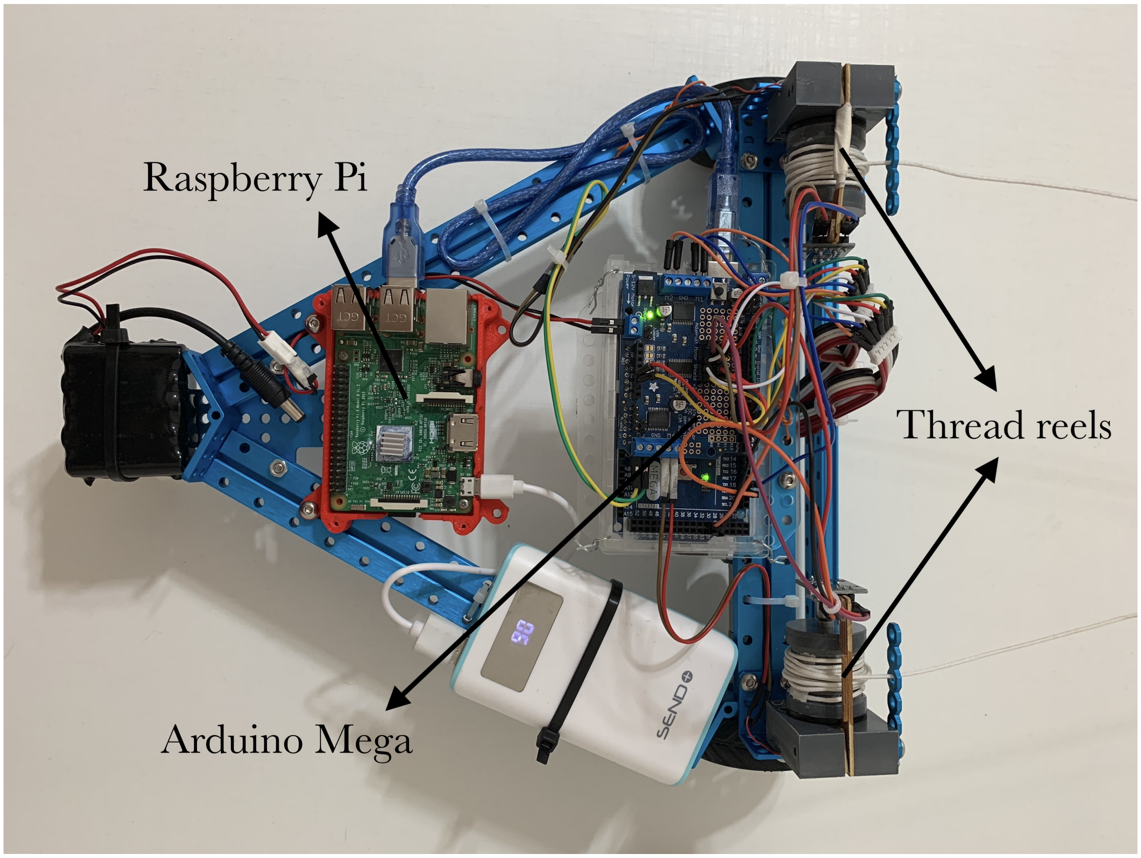
Two simple control strategies are proposed and evaluated. The first one is called Follow-the-thread and the second strategy is Rotate-And-Go. The Adafruit Shield controller provides a very stable output signal, provided battery are kept above reference. Hence, wheels motor control is open-loop.

III. Experimental Protocol

This section describes the experimental protocol used to evaluate the performance of the proposed solution. The Pulmonary Rehabilitation procedure consists on a series of walking activities aimed to promote patient muscular recovery and well being [2]. They are slow pace motions following a specific trajectory on a rehabilitation gym.

In order to standardize the procedure [18], the *Lemniscate of Gerono* is used as desired trajectory, a curve shaped like an ∞ symbol, described by the Equation 1:

$$\begin{aligned} &x(\phi) = a\ cos(\phi) \\ &y(\phi) = a\ cos(\phi)\ sin(\phi) \\ &where\ \phi \in \{-\pi, \pi\} \end{aligned} \tag{1}$$



(a) Case I

Fig. 3: Robot prototype built to evaluate the real world scenario of described following mechanisms for the tethered robot.

where ϕ is the free parameter, and x and y determine the shape of the trajectory on the navigation plane.

The reason this shape was chosen is because it combines different kinds of trajectories that we want to test the vehicle in: long straight segments, sharp and soft curves, all in one single shape. Similar curves are also used in other proposed experiments in [4], [12]. Regarding metrics, three are proposed to evaluate the performance. They are

- *Normal path deviation*: the subject trajectory is divided into small segments and then the normal distance to the robot trajectory is calculated for each of those segments. Path deviation is relevant to evaluate how closely the robot mimics the leader path, which is the ultimate goal of the robotic vehicle.
- *Maximum path deviation*: the maximum *normal path deviation* registered during an experiment.
- *Total path deviation*: The area under the curve resulting from the the *normal path deviation* over the length travelled by the leader.
- *Robot-leader distance*: The euclidean distance between the robot and the leader, at any point in time. This is particularly important since the robot has a limited amount of thread available, so if the leader uses all the available thread, it will start dragging the robot and damaging the following mechanism. It is a scenario that must not happen under any circumstance, as it can also be dangerous for a potential patient using the device.

In this work, a *following behavior* is considered satisfactory if its maximum path deviation is less than 0.75 m and the robot-leader distance never exceeds 1.5 m [19].

First the simulation is described and later the evaluation on the robotic prototype is detailed.

A. Simulation

A model of the proposed design was first built on Webots application. The threading mechanism was implemented using virtual threads [9]. The leader traveled according to a predefined path with constant velocity, followiing the lemniscata trajectory.

The simulation is also useful to study the effects of the different constants in each strategy on the movement of the robot.

B. Real world

A real world experiment was performed, begging to maintain the same conditions implemented on the simulation environment. A lemniscata of $a = 1m$ was drawn on the floor on the visual capturing room.

IV. Results

Simulation results for both control strategies are shown on Figures 1 and 2.

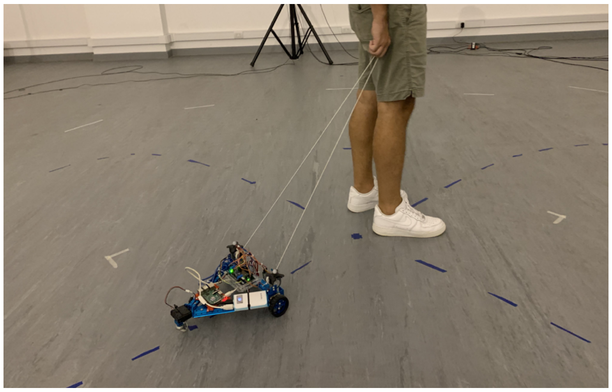


Fig. 4: Trajectory for the Follow-The-Thread control strategy.

Results metrics for the simualtions are shown on table 1.

c_v	c_α	Max path deviation [m]	Area under *npd* curve
10	15	0.3614	2.0651
15	5	0.4325	2.055
15	**10**	**0.2188**	**1.0902**
15	15	0.2891	1.5059
5	20	0.5733	3.7289

TABLE I: Normal path deviation and maximum path deviation for different Follow the Thread constants.

c_v	c_r	Dt_{off} [m]	Max path deviation [m]	Area under *npd* curve
10	20	0.1	0.4310	1.6380
20	20	0.05	0.7775	3.1139
20	**20**	**0.1**	**0.4123**	**0.9872**
20	35	0.1	0.4143	1.4820
20	5	0.05	0.7815	3.0892
35	20	0.1	0.6337	1.6190

TABLE II: Normal path deviation and maximum path deviation for different Rotate and Go constants.

Additionally, speed profiles can be observed from both trajectories.

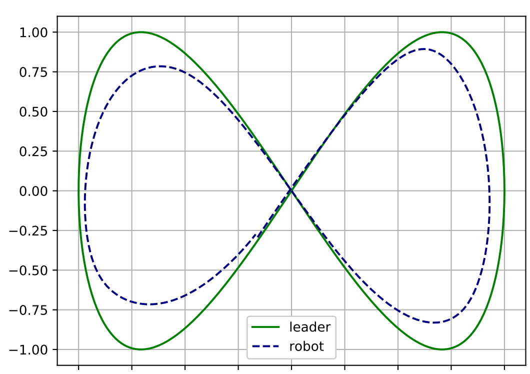


Fig. 5: Trajectory for the Follow-The-Thread control strategy.

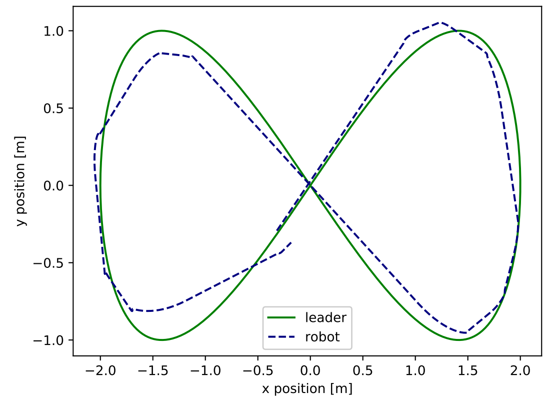


Fig. 6: Trajectory for the Rotate-And-Go control strategy.

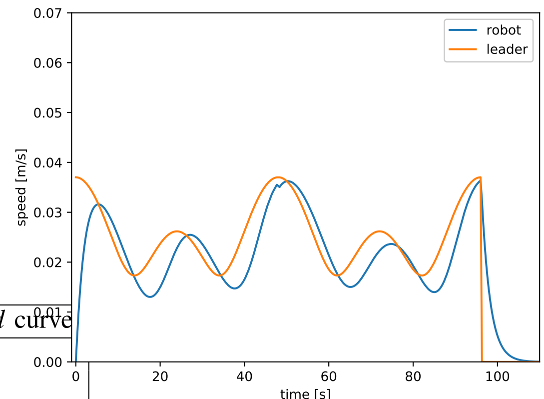


Fig. 7: Follow-The-Thread.

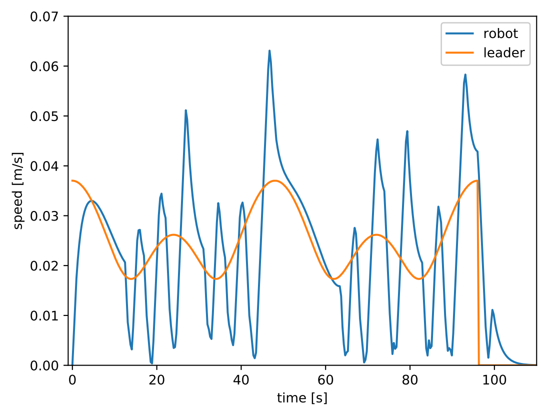


Fig. 8: Speed profiles for Rotate-And-Go.

Results for the real world experiment can be seen on Figures 3 and 4.

c_v	c_α	Max path deviation [m]	Area under *npd* curve
25	20	0.3876	1.9761
25	35	0.4672	2.3528

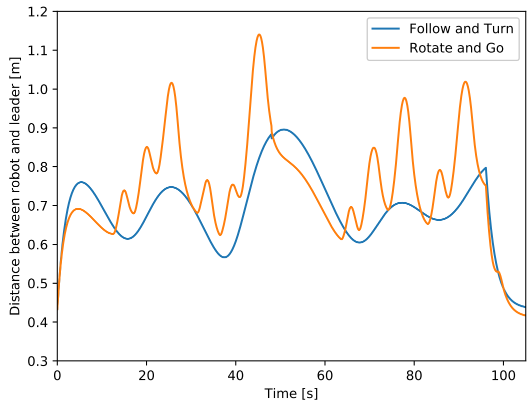


Fig. 9: Distance between robot and leader [m]

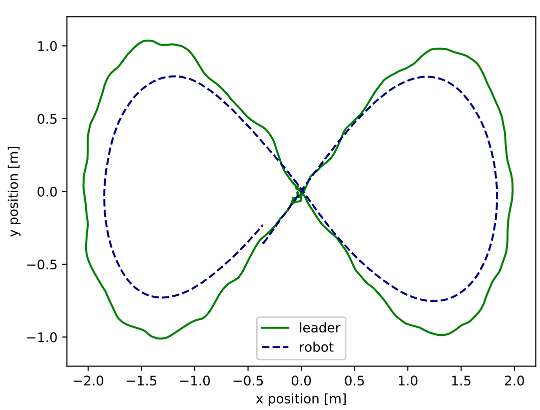


Fig. 10: Trajectories for the Follow-The-Thread control strategy.

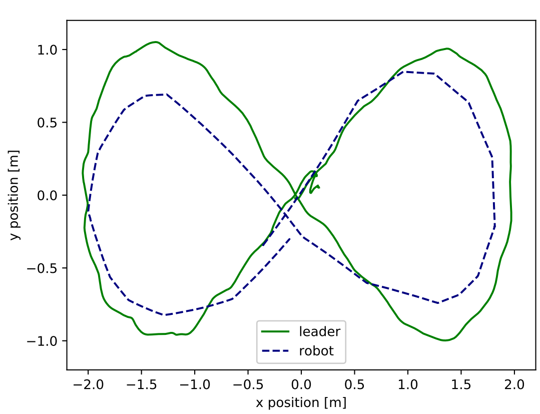


Fig. 11: Distance between robot and leader [m]

TABLE III: Normal path deviation and maximum path deviation in motion capture experiments using Follow the Thread.

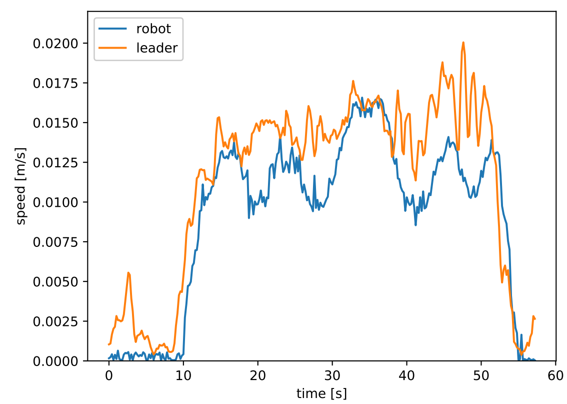


Fig. 12: Follow the thread speed profiles

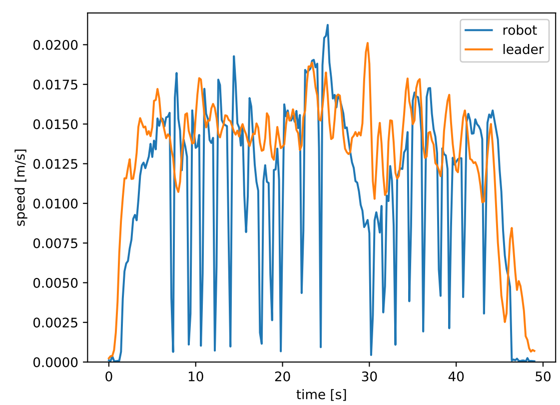


Fig. 13: Rotate and Go speed profiles

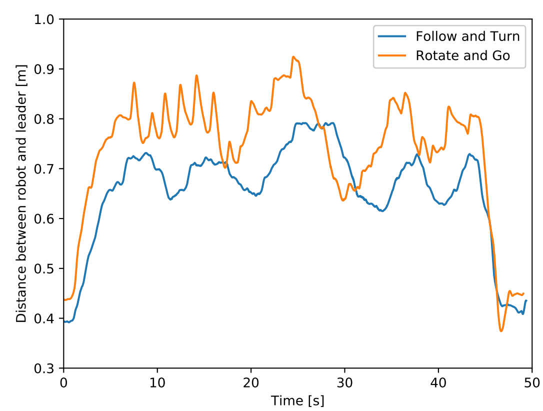
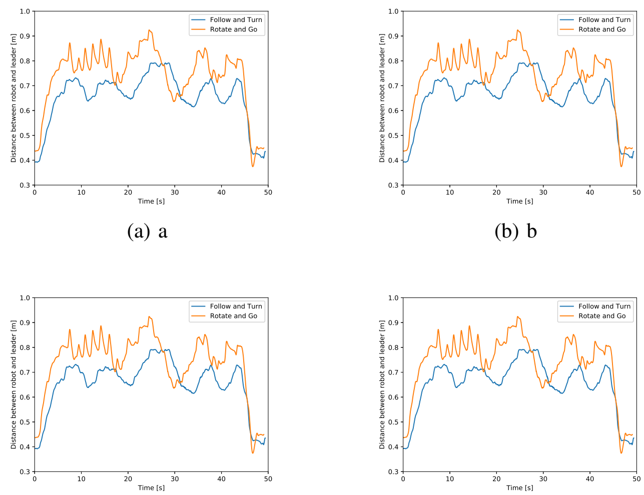


Fig. 14: Rotate and Go speed profiles

c_v	c_r	Dt_{off}	Max path deviation [m]	Area under *npd* curve
30	35	0.04	0.4116	2.8309
30	35	0.08	0.3739	2.0367

TABLE IV: Normal path deviation and maximum path deviation in motion capture experiments using Rotate and Go.



(a) a (b) b

(c) c (d) d

Fig. 15: (a), (b) Some examples from CIFAR-10 [**?**]. The objects in single-label images are usually roughly aligned.(c),(d) However, the assumption of object alignment is not valid for multi-label images. Also note the partial visibility and occlusion between objects in the multi-label images.

V. Discussion

A. Clinical Assessment

No amount of metrics are enough to evaluate if the robot is a viable solution for this problem or not, without the input and the evaluation of the people that are going to physically make use of it.

As this project is a joint research between ALPI and ITBA, we invited 4 people from the ALPI staff, 3 doctors and one engineer, to the motion capture laboratory at ITBA, where we made a live demonstration of the robot working and following a moving person.

In the demonstration, we described how the robot worked, how it was built and how to operate it. Both control strategies were explained, along with the main superficial differences between them.

Afterwards, we invited the doctors to use the robot themselves, simulating they were the patient being followed. We let the doctors switch between the two control strategies to evaluate both of them, and made different tests, one walking along path drawn in the floor (figure **??**), and another one walking freely in the space available in the lab. We let them use the robot as long as they wanted to, to get a general idea of how it behaved, and how it could be used in the rehabilitation process. After all evaluations were finished, we answered questions and discussed various aspects of the vehicle prototype with the ALPI staff, and then proceeded to ask them a survey to document their experience with the robot, get their expert opinion on how the two strategies compared against each other, and what other improvements were needed in order to deliver a fully usable product.

According to their answers, and the discussion we had after testing the robot, the general opinion was that the *Follow the Thread* strategy was safer and more convenient for the task. In the survey, when asked *Which of the two strategies is more effective at following the patient in a rehabilitation exercise?*, all 4 people responded that *Follow the Thread* is ”much better”.

The main concern with the *Rotate and Go* strategy was that having to wait for the robot to rotate before moving forward might be unsafe, as the patient could move away from it and compromise the cannula connecting him or her to the oxygen tank. This issue was identified during our own tests, and was not mentioned when explaining the following mechanism to the doctors, to avoid skewing them. They independently identified this problem, and emphasized that it could be a great source of discomfort for the patient.

Another aspect that was value from the *Follow the Thread* strategy is that since its smoother movement, with no sudden stops or accelerations, was favorable for the stability of the robot if it were to carry the heavy oxygen tank.

Two needed security measures were also brought up by the ALPI team. Firstly, the need to add some mechanism for obstacle avoidance. They mentioned the need to have sensor to detect if the robot was about to hit something (specially the patient), and stop immediately, apart from what the control strategy indicated. Secondly, they recognized that some patients have very weak stability, and might fall down or take a step back, towards the robot, so it should be able to automatically move away from the patient, in order not to become another obstacle for him or her. ”Tener en cuenta la distancia a la que se encuentra el robot por si el paciente llega a dar un paso atrás - para evitar riesto de caída’” and ”Estaría bueno pensar en algún método de emergencia por caída” were two quotes related to this issues, taken from the surveys.

In order to have more information for the next steps in the development of the robot, we asked for their advise to design the mechanism to attach the threads to the patient being followed. Two ideas were proposed: a belt strapped to the patient waist, or a clasp that would also to the clothes of the patient, also near its waistline. The waist is a good attachment point, since it is relatively stable when the patient moves, compared to its hands or legs, that may make sudden movements and confuse the robot sensors.

B. Conclusion and Future Work

The goal of this work is to verify if a tethered robot to implement a following scheme on a patient during a pulmonary rehabilitation procedure is too simplistic to be a factual implementation.

From the practical experiments we showed that the both algorithms gave reasonable following performance in task of following the leader along a lemniscate-shaped path. This research is that this performance was achieved using very low cost components. It was proven that a reasonable following behaviour could be accomplished with a simple mechanism, a characteristic that significantly lowers the price of a device like this, putting it within reach of many medical institutions.

Each control strategy has its advantages, but according various metrics described in this work, the *Follow and Turn*

Question	Avg. answer
How would you qualify, from 1 to 5, your overall experience with Follow the Thread? (1:Bad, 5:Excellent)	5.0
How safe would a patient be, from 1 to 5, being followed by the robot using the Follow the Thread strategy? (1:Very unsafe, 5:Very safe)	4.25
How would you qualify, from 1 to 5, your overall experience with Rotate and Go? (1:Bad, 5:Excellent)	3.5
How safe would a patient be, from 1 to 5, being followed by the robot using the Rotate and Go strategy? (1:Very unsafe, 5:Very safe)	3.25

TABLE V: Answers to survey questions.

strategy had a more desirable behaviour, as it tended to follow the leader from a closer distance at all times, while moving in a smooth and predictable way.

We understood that no metric is enough to evaluate how appropriate the robotic vehicle can be for a real life scenario. Therefore, we gathered feedback from healthcare professionals from ALPI, who provided us with invaluable feedback to evaluate our solution. Over all, they also valued the Follow and Turn strategy as being the safer and more effective one. Most importantly, they also validated the research made and approved the direction of the project. They proposed a series of improvements and next steps, and after seeing the prototype in action, believed that we were close to a real, working solution.

It is essential to involve stakeholders such as patients, doctors, nurses, and any other professionals involved in the rehabilitation process early in the design roadmap. They are the ones who understand the problem better than anyone else, and will be the end users of a product like this.

The staff at ALPI was enthusiastic about helping in the development of the robot, and their encouragement and support were the key reasons we could take this project forward. This work not only made progress from a technical standpoint, but could also become the foundation of a long-term relationship of collaboration and research between ALPI and ITBA. This is also the start of a long-term project at ITBA. One that can go on to become a complete, real world solution that can improve the quality of life of many people through the use of technology and engineering.

C. Future Work

A following mechanism has been designed and implemented in a hardware prototype. The mechanism, along with the two control algorithms, has shown promise to be a viable solution to implement in a functioning robot that ALPI, or any other medical institution, can use in their every day exercises with COPD patients.

The next steps for this project would be to take this prototype and build a bigger version, with motors powerful enough to carry a real oxygen tank.

Further research is also needed to develop a full fledged solution:

- Power the motor wheels with a *closed-loop and more efficient controller*, to have a more precise control over their speed.
- Redesign the active spring mechanism in the reels to avoid overheating. In our tests, the small electric motors in each reel got very hot after just 20 minutes of use. The algorithm we designed to use them more efficiently (**??**) was enough to keep them in manageable temperatures (under 70^0C), which was enough for testing the prototype, but would not be appropriate for a useful robot. Not only because the heat produced can be dangerous, but also because the motors can overheat and break their insulation in regular use.
- An easy and safe interaction between the patient, the operator and the robot. How to communicate the state of the robot to the operator, how to control and manipulate the robot in an effective and user-friendly way.
- Safety measures to keep the patient and the doctor or nurse safe when using the robot. Not only safe from the robot movement, but also from its electronic components, which can be dangerous when used near the pure oxygen tank if they are not protected properly.
- Investigate and design mechanisms for obstacle avoidance. This need was emphasized by the doctors from ALPI. The robot should have mechanisms in place to deal with emergency situations, and under no circumstance it can hit the patient or the doctor operating it.
- Achieve a battery autonomy that makes the robot useful throughout a complete pulmonary rehabilitation exercise. It is crucial for its usefulness to be able to hold a charge for this period of time, along with the ability to quickly swap batteries if the vehicle will be continually used with different patients.

VI. Acknowledgments

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Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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