A Control Strategy for a Tethered Follower Robot for Pulmonary Rehabilitation

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***Abstract*—Patients that suffer Chronic Obstructive Pulmonary Disease (COPD) undergo a procedure called Pulmonary Rehabilitation that helps them to improve disease prognosis. During Pulmonary Rehabilitation procedures patients require oxygen assistance. The oxygen tank cannot be carried by the patient and external assistance is required. This work provides an initial study on the controlling mechanism of a differential tethered robot that implements a leader-follower configuration to carry the oxygen tank for Pulmonary Rehabilitation procedures. Two alternative control strategies are proposed. Results are simulated and tested on a real prototype in a Motion Capture System.**

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

I. Introduction

CHRONIC Obstructive Pulmonary Disease (COPD) is an umbrella term that describes several pulmonary affections. They are characterized as a slowly progressive condition marked by airflow limitation, being cigarette smoking the main etiologic factor [1]. This pathology presents an eskeletomuscular atrophy [2], [3] and 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 present a severe low oxygen saturation illness and they require effective oxygen supply, particularly when performing physical activity [4]. 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 are required to improvise 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 [5] 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 looks forward for the development of robotic affordable solutions to the social and health-related worldwide problems [6].

For the implementation of the leader-follower strategy, several solutions have been proposed, including Simultaneos Localization And Mapping (SLAM) alternatives, vision-based systems or based on electromagnetical beacons [7]. The work presented by [8] 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 [9]. 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 [10], [11], [12].

On the other hand, several assistance devices for COPD treatments have been proposed. Particularly relevant are novel telemedice applications to enhance complementary rehabiliation exercise at home that can track biological markers for patients [13], [3]. The work presented here follows the line established by [14]. 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 facilities.

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. To do so, this document unrolls as follows. Section II poses the problem and the solution design. Section III documents 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

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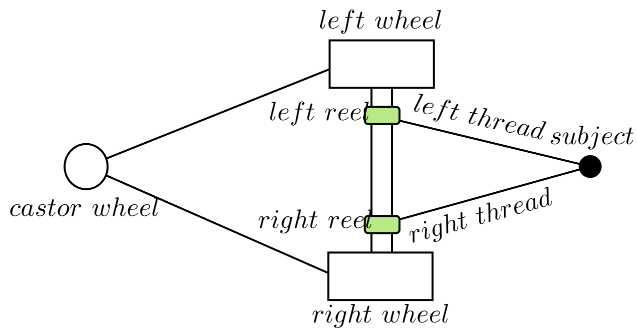


Fig. 1: Components of the robotic vehicle and following mechanism

with medical personnel is tackled in Section V-A. Finally, conclusions are exposed in the remaining section V-B.

II. Materials and Methods

To be effective, any technological solution for the medical community requires active involvement of key stakeholders: physicians, care-givers, patients and their families [15], [16], [17], [18], [19]. Hence, design methodologies that allow rapid prototyping can bring quickly feedback from real users about drawbacks or opportunities for improvements.

Looking forward to achieve this goal, a basic robotic configuration is designed that allows the implementation of the tethered controlling mechanism, while keeping away other necessary features that will be the focus of future iterations. This design is first simulated in a simulation environment, and later, a basic hardware prototype based on Internet of Robotic Things [20] is built to verify the design guidelines and assumptions on a real world scenario.

A. Solution Design

The proposed solution is a Differential-Wheeled Robot (DWR) tethered to the followed subject with two threads ending at a single point attached to the subject waist, back or hand. In the same axis as the two front wheels, the robot has two reels separated by a certain length from which these threads come. As the subject moves away from the robot, the reels release thread so that the patient does not physically drag the vehicle. When the opposite happens, and the vehicle gets closer to the subject, an active spring mechanism driven by electric motors move each reel to retract the thread. The threads need to be tense at all times so that the encoders in each reel can be used to continuously measure the distance between the subject and the reel as devised in Figure 1.

Encoders in each reel measure the difference in length of each thread compared to its initial position. This difference in length is the input for the control algorithm. Using the encoder, the difference in length of the thread can be measured with this formula:

$$L_d = pulses.\frac{2\pi r}{ppr} \tag{1}$$

The variable r is the radius of the reel and ppr is the pulses per revolution (resolution) of the encoder. The initial position of the threads is configurable.

B. Hardware

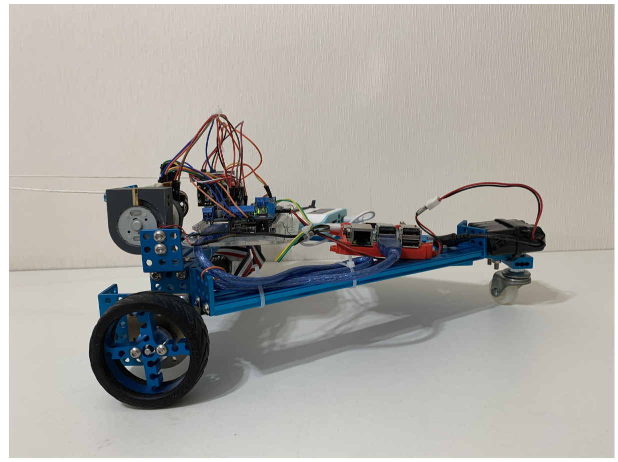


Fig. 2: Side-view of the robot prototype. A differential wheel, the reel and the rear free castor wheel can be observed from the picture.

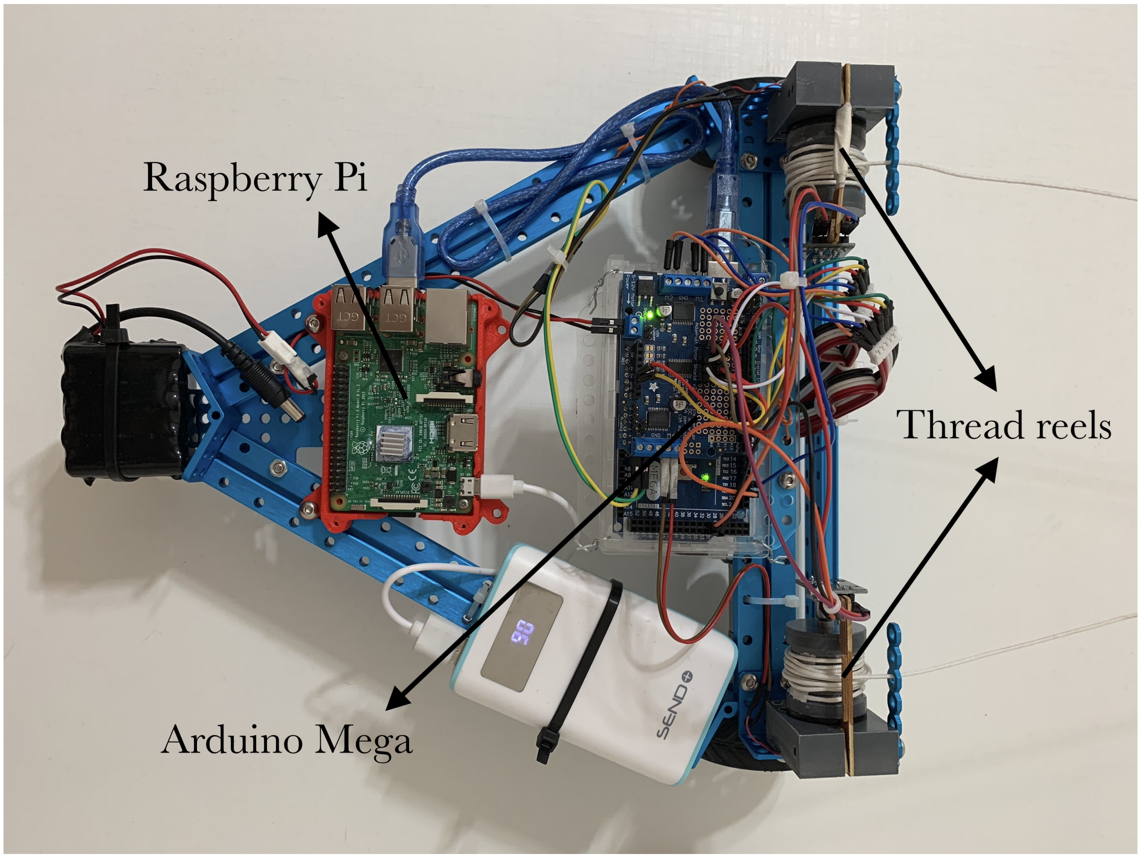
Frames are constructed from aluminum extrusions produced by Makeblock (Shenzhen, China). The prototype is a three-wheeled robot with two frontal differential drive wheels and a free castor wheel as a third point of contact on the back, as can be seen on Figure 3.

Two motors Makeblock Optical Encoder Motor-25 9V/86 rpm are used on in-wheel configuration providing optical encoding. A microcontroller Arduino (Arduino LLC, Italy) Mega 2560 is used to implement the control loop and to provide encoder processing. On top of it an Adafruit (Adafruit, New York City) Motor Shield v2 bridge is used to drive the four DC motors, one for each wheel and one on each reel. The Arduino board is also connected to a Single Board Computer Raspberry Pi (Raspberry Pi Foundation, United Kingdom) 3B+ through serial connection on the USB port.

The Raspberry Pi board connects to a WiFi network and can receive remote commands to control the robot. It also broadcasts telemetry data to any listening devices on the network. The control algorithms run in this board, which continuously communicates with the Arduino board to receive sensor data and to issue commands to move the motors or retract the reels. The algorithms are programmed in python 3.7, which allows the exact same code to run both the simulated and real world prototype.

The two reels are designed from PVC extrusions and are shown on Figure 3. They are attached to regular FA-12350 DC motors scavenged from old compact discs. Each reel is axially locked to inexpensive Ky-040 rotary encoder which provides around 20 pulses per revolution.

The prototype can be seen on Figure 2 and 3. It has two separate batteries, one powering the Raspberry Pi, the Arduino board and the encoder electronics, and the other powering the drive and reel motors. The first battery is a commercial power



(a) Case I

Fig. 3: Top view of the robot prototype. The SBC is shown on the center, alongside the Arduino Mega board. Both reels can be seen on the same vertical plane of the wheel axis. A power bank (white) is located on one side of the robot, and on the rear part, the motor power battery (black) is located.

bank with a capacity of 10000 mA·h, and an output of 3.1A (over two USB ports) at 5V. The motor battery is a set of 10 AAA nickel–metal hydride batteries (1.5V each), with a total output of 15V.

C. Active Reel Spring

As previously mentioned, an active spring mechanism is also put in place to keep the threads tense. However, in order to extend the useful life of the reel motors, and to save battery, an algorithm to activate and deactivate the motors is 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. Control Strategy

Two simple algorithmic control strategies are proposed and evaluated. The first one is called Follow-the-thread and the second strategy is Rotate-And-Go.

1) Follow the Thread: This control strategy is similar to the one presented in [8]. It is based on the idea that the difference in length between both threads provides a quasi-linear function of the relative angle between the subject and the vehicle orientation and, additionally, the mean of both thread length allows to approximate the relative distance between the robot and the subject. They are described by Equations 2, 3 and 4.

$$v_{tar} = c_v\left(\frac{D_l + D_r}{2} - d_0\right) \tag{2}$$

$$vleft_{tar} = v_{tar} + c_\alpha(D_l - D_r) \tag{3}$$

$$vright_{tar} = v_{tar} - c_\alpha(D_l - D_r) \tag{4}$$

where c_v and c_α are constant coefficients used for calibration. As shown in Figure 4, reel encoder information is D_l and D_r for the left and right reel, and finally $vleft_{tar}$ are $vright_{tar}$ are the power values that are directly used to drive power to each wheel motor.

To stop the vehicle completely when it is close to its expected position, an additional condition is added:

$$\textit{if } \frac{D_l + D_r}{2} < d_0 \textit{ then } vleft_{tar} = vright_{tar} = 0 \tag{5}$$

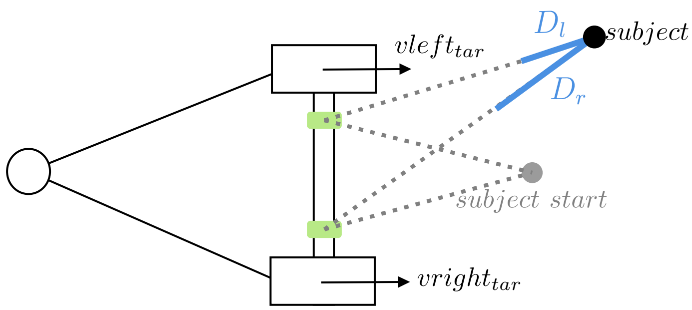


Fig. 4: Following mechanism parameters

where d_0 is a constant offset that is used to customized the length of the thread where the robot does not move.

2) Rotate and Go: The *Rotate and Go* algorithm divides the vehicle movement in two steps:

- Rotating the vehicle around the center point of the axis that connects its front wheels in order to aim at the subject.
- Go forward in a straight line until the vehicle is at the expected distance to the subject or the vehicle is not moving in the direction of the subject.

The procedure is detailed in Algorithm 1. The variable V_r is the speed at which the vehicle will rotate on its axis, and V_f is the speed at which the vehicle will move forward once it can move on the subject's direction. The algorithm requires three parameters, c_v and c_r that regulates the coefficients for the forward and rotation movement, and an additional parameter Dt_off that regulates the sensibility of the rotation movement.

$Dt \leftarrow D_l - D_r$
$Dm \leftarrow \frac{D_r+D_l}{2}$
$V_r \leftarrow c_r * (abs(Dt) - Dt_off) + base_{vr}$
$V_f \leftarrow c_v * (Dm - Dm_off)$
if $abs(Dt) > Dt_{off}$ **then**
  if $D_l > D_r$ **then**
    $vleft_{tar} \leftarrow V_r$
    $vright_{tar} \leftarrow -V_r$
  else
    $vleft_{tar} \leftarrow -V_r$
    $vright_{tar} \leftarrow V_r$
  end if
else
  if $D_m > Dm_{off}$ **then**
    $vright_{tar} \leftarrow V_f$
    $vleft_{tar} \leftarrow V_f$
  else
    $vright_{tar} \leftarrow 0$
    $vleft_{tar} \leftarrow 0$
  end if
end if
Return $vright_{tar}$ and $vleft_{tar}$.

Algorithm 1: Rotate and Go algorithm

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 [3]. They are slow pace motions following a specific trajectory on a rehabilitation gym.

In order to standardize the procedure [21], the *Lemniscate of Gerono* is used as desired trajectory, a curve shaped like an ∞ symbol, described by the Equations 6:

$$\begin{aligned} &x(\phi) = a\ cos(\phi) \\ &y(\phi) = a\ cos(\phi)\ sin(\phi) \\ &where\ \phi \in \{-\pi, \pi\} \end{aligned} \tag{6}$$

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 where the vehicle can be tested: long straight segments, sharp and soft curves, all in one single shape. Similar curves are also used in other proposed experiments in [5], [14].

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 [22].

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 [23] simulator. The threading mechanism was implemented using virtual threads [10]. 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. The leader starts at the midpoint of the trajectory and completes a full complete circuit getting back to the initial position, while the robot follows its track. Four different configuration sets of c_v and c_α were tested for Follow-The-Thread, while 6 different configurations were tested for Rotate-And-Go.

B. Real world

A real world experiment was performed, pegging to the same conditions implemented on the simulation environment. A motion capture system is used to track the movement of a human leader along a predetermined path. The motion tracking system consists of an array of 16 OptiTrack (NaturalPoint Inc, Oregon, US) Flex 3 cameras, which measure the position of reflective markers with an accuracy of ± 1 [cm] at sampling rate of 100 Hz. The calibration and data collection was made using the Motive motion capture software.

A tracked marker was placed in each side of the robot (on top of each thread reel). The human leader used his hand to grab the tip at which the two tethers were tied together. A third marker was placed in his hand, using a glove. The lemniscate of Gerono, used in the simulation, was marked on the floor, and the human leader tried to move his hand following this shape as close as possible, with stable speed. The shape was marked according to the shape described in Equation 2, using $a = 2$ [m].

The three markers allowed to measure the trajectory of both the robot and the leader, and then obtain the same metrics calculated in the simulation. Four experiments were performed for each set of parameter configurations. In this case, only two set of configuration were tested for each strategy.

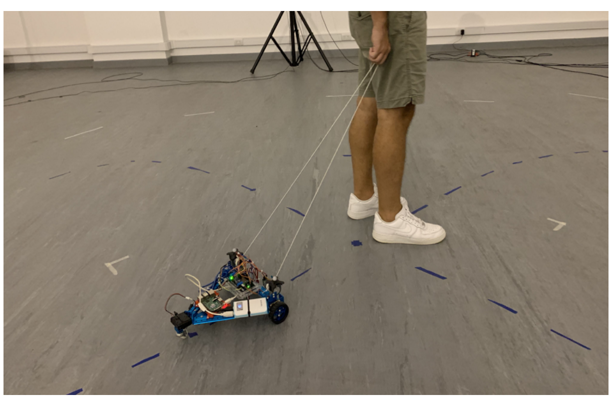


Fig. 5: Hardware prototype on the motion capture system and a testing subject holding the threads. The lemniscata of gerone was marked on the floor. The subject follows this track on the experiments performed.

IV. Results

Simulation results for both control strategies are shown on Figure 6. Results metrics for the simulations are shown on Table I for the Follow-The-Thread strategy, whereas metrics for Rotate-And-Go are shown on Table II.

c_v	c_α	m.p.d.	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: Max path deviation m.p.d. [m] and Area under the normal path deviation for different Follow the Thread constants.

c_v	c_r	Dt_{off}	m.p.d.	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: Max path deviation m.p.d. (in [m]) and area under normal path deviation for different Rotate and Go constants.

Additionally, speed profiles can be observed from both trajectories.

Results for the real world experiment can be seen on Figure 7. Table III show the metrics of the Follow-The-Thread strategy, whereas Table IV provides the metrics for the Rotate-And-Go approach.

c_v	c_α	m.p.d. [m]	Area under *npd* curve
25	20	0.3876	1.9761
25	35	0.4672	2.3528

TABLE III: Max path deviation m.p.d. and area under normal path deviation in motion capture experiments using Follow the Thread.

c_v	c_r	Dt_{off}	m.p.d. [m]	Area under *npd* curve
30	35	0.04	0.4116	2.8309
30	35	0.08	0.3739	2.0367

TABLE IV: Max path deviation m.p.d. and area under normal path deviation in motion capture experiments using Rotate and Go.

V. Discussion

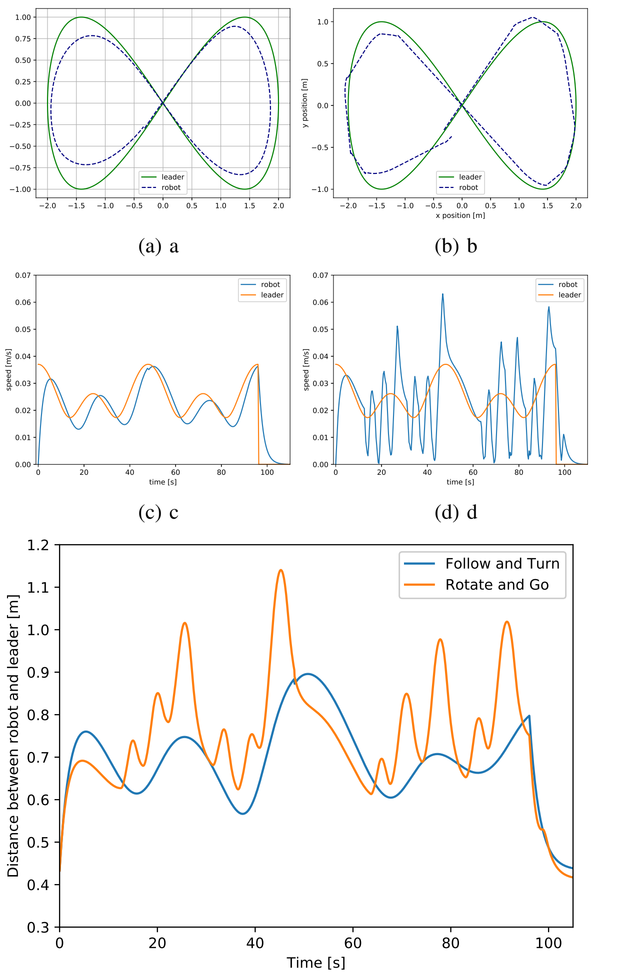
A. Clinical Assessment

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.

ALPI is a non-profit civil association located in Buenos Aires, Argentina, that provides neuromotor rehabilitation for pediatric and adult patients. It was founded in 1943 with the main focus of treating children with poliomyelitis, and has since expanded to deal with all kinds of related diseases.

Four professional care-givers from ALPI were invited to test and evaluate the controlling strategy on the prototype. A live demonstration of the robot working and following a moving person was performed.

In the demonstration, the robot design was outlined and an explanation was given on how the robot worked, how

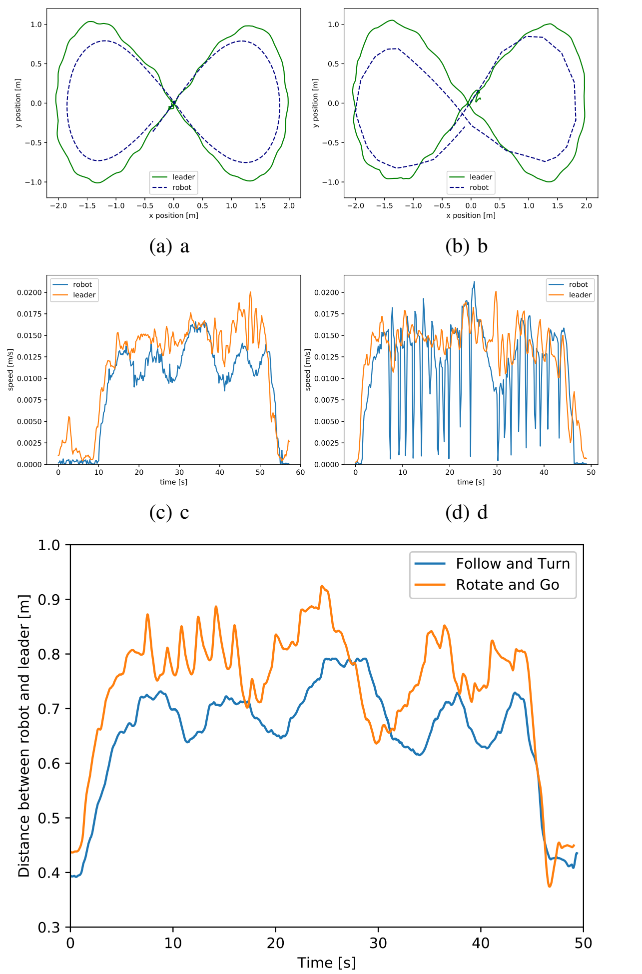


(a) a (b) b

(c) c (d) d

(e) d

Fig. 6: Simulation Results: Trajectories of the leader and follower for Follow-The-Thread (a) and Rotate-And-Go (b) . Speed profiles of the leader and follower for Follow-The-Thread (c) and Rotate and Go (d). (e) Separation distance between robot and leader for both strategies [m].



(a) a (b) b

(c) c (d) d

(e) d

Fig. 7: Experimentation Results: Trajectories of the leader and follower for Follow-The-Thread (a) and Rotate-And-Go (b). Speed profiles of the leader and follower for Follow-The-Thread (c) and Rotate and Go (d). (e) Separation distance between robot and leader for both strategies [m].

it was built and how to operate it. Both control strategies were expounded, along with the main superficial differences between them.

Afterwards, health care professionals were invited to use the robot themselves, simulating they were the patient being followed. They were allowed to switch between the two control strategies to evaluate both of them, and made different tests, one walking along standardized path marked on the floor and another one walking freely along the available space of the Motion Capture Lab . They used the robot freely to get a general idea of how it behaved, and how it could be used in the rehabilitation process. After all evaluations were finished, various aspects of the vehicle prototype were discussed and then a survey was handed out 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. Survey questions and their averaged numerical evaluations are provided in Table V.

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

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.

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 sensors 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.

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 tied to the clothes of the patient, also near its waistline. The waist is a good attachment point, since it is relatively more 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

From the practical experiments, it is verified that the both algorithms gave reasonable following performance in the task of following the leader along a lemniscate-shaped path. This reasonable following behaviour is accomplished with a simple mechanism, a characteristic that significantly keep the price of the device low, 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* 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.

Insightful feedback is gathered from healthcare professionals from ALPI, who provided invaluable data to evaluate the solution. Over all, they highlight the Follow and Turn strategy as being the safer and more effective one. Most importantly, they also validated the research and were enthusiast about the direction of the project. They proposed a series of improvements and next steps after seeing the prototype in action.

As described in the beginning, 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 any developed product, as long as it is useful for them.

The staff at ALPI was enthusiastic about helping in the development of the robot, and their encouragement and support are key reasons to take this project forward. There are yet many challenges ahead, but these initial results are promising about the viability to develop a real world solution that can improve the quality of life of many people through the use of technology and engineering.

C. Future Work

The next steps for this project is to scale the design to be able to carry safely the oxygen tank.

Further research is 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 active reel algorithm is enough to keep them in manageable temperatures (under 70^0C), which is enough for testing the prototype, but it will 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 care-giver safe when using the robot. Not only safe from the robot movement, but also from its electronic components.
- An obstacle avoidance subsystem. This necessity is emphasized by the personnel 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.

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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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