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Supporting elderly's independent living with a mobile robot platform

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Abstract: With the increased aging population, and declined support from the families, societies will need new tools to ensure the well-being of the elderly. Many of them would prefer living at home, but they will need help and assistance from someone. Technological innovations in the field of robotic systems can be used to enable independent living, to prolong the life of the elderly in their familiar home environments, to maintain the social connections by reducing social isolation and to improve the quality of life in general. In this paper, we present the design and validation of a low-cost mobile robot system that can assist elderly and professional caregivers in everyday activities. The robot structure and its control objectives are described in detail. The developed assistive telepresence robot was tested in simulation and experimentally. On field experiments were conducted in real environment, with potential end users, which is a major advantage of this study. The results of the evaluation were very satisfactory and have shown that participants can operate the robot safely and efficiently. The participants were very satisfied with the performance and features of the robot.

Keywords: assistive robotics, elderly care, mobile robot system, shared control, telepresence robot.
Categories: J.0, J.6
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1 Introduction

The rapidly growing population of elderly people raises some important issues such as adequate health care for the elderly [WHO, 2021]. Since the process of ageing is accompanied by the loss of certain motor and cognitive abilities, there is an increasing need for long-term care and daily assistance for the older people [WHO, 2015]. Healthcare provided by human professionals is the dominant and preferred type of care, but due to the lack of qualified health care personnel, additional assistance is also needed.

Assistive robotic technologies could be an interesting option for addressing this problem in the healthcare system, supporting elderly's independent living and aging in place. They can make a significant difference in the lives of the elderly and their caregivers. For older people, remaining in their home instead of living in an elderly care facility, is very important and beneficial for their quality of life [Perez, 2001]. Robotic assistants can enhance the autonomy level of older people thus prolonging the nursing home admission. They can help people remain healthy and safe in their own homes, ensuring their independence in everyday life [Mitzner, 2014].

Assistive robots for elderly people can be broadly categorized into two groups [Broekens, 2009]: rehabilitation robots – designed to assist people with cognitive, sensory or motor impairments [Tejima, 2001] [Koceska, 2013], and assistive social robots, which include, companion robots and personal service robots. Companion robots aim to enhance the health and psychological well-being of the older people [Shibata, 2012] [Robarts, 2015] [Leite, 2008]. They keep company to the elderly thus reducing the loneliness and social isolation which are the common problems for this category of people. Personal service robots are robots that operate semi or fully autonomously and are usually operated by a lay person [IFR, 2021]. Automated wheelchairs, vacuum cleaning and lawn-mowing robots, telepresence robots, servant robots, elder care, and entertainment and leisure robots are just a few examples of personal service robots.

The market of this category of robots is anticipated to expand remarkably at a robust CAGR (Compound Annual Growth Rate) of over 31% during the period 2019-2021, with predicted sale of 34,400 units for the mention period [IFR, 2018]. The increasing demand of personal service robots has accelerated the research done in this field.

Many personal service robots currently available on the market are designed to perform specific routine tasks, such as: eating, drinking, maintaining a shopping list, reminder for taking medications, emergency notification and navigation (PEARL [Pollack, 2002], CompanionAble [Schroeter, 2013], CareBot [Sharkey, 2011], Kompai [Kompai, 2021]). Other robotic systems, like Giraff [Cesta, 2010], VGo [VGo, 2021], Anybots [Anybots, 2021],) are mobile telepresence systems, specifically designed for social interaction. These telepresence systems are equipped with a videoconferencing set (including camera, microphone, speaker and screen), allowing a person to be virtually present at the elderly's residence and to move around as if he/she was physically there. There are very small number of developed robot systems that support a wider range of informational and physical tasks in order to help older people in daily activities. Care-o-Bot [Care-o-Bot4, 2021], PR2 [Garage, 2009], Twendy-One [Iwata, 2009] are the only robot systems that have manipulator capabilities. For this purpose, they are equipped with one or two arms that are used for grasping and manipulating objects in various environments. This is considered a very important feature, highly preferred by the elderly [Mast, 2010] [Bedaf, 2017]. However, the manipulator capabilities increase the price of the robot. For example, the configuration of the PR2 robot with a single arm costs about $285000 and its double arm variant about $400000. Twendy-One (previously known as Wendy) costs between $100000-$200000. In addition to the high cost, these robots have their own limitations, such as: the absence of both social and healthcare capabilities as well as problems with thresholds during indoor navigation.

Having in mind the limitations of the existing solutions, as well as the needs of the older people, we have designed and developed a low-cost mobile telepresence robot system that can assist and support elderly in certain activities of daily living and care. The main advantage of this system is its multifunctional capabilities as well as its cost. Developed robot prototype costs several times less than the price of the above mentioned commercial robots.

The robot is designed following the user-centered methodology and implements multiple functions such as: safe navigation, fetch and carry small objects, reminder, calendar and interpersonal communication. It can be used by both elderly and caregivers. The robot has been evaluated in several experimental scenarios and the results are reported in this study.

2 Design of the developed robot

2.1 Design methodology

The robot was developed using Design Thinking (DT) methodology [Plattner, 2012], which is a human-centered approach to solving problems. DT match people's needs (in our case elderly and caregivers) with what is technologically feasible at the moment. The process is iterative in nature and consist of five stages: empathize, define, ideate, prototype, and test.

At the heart of design thinking are empathy and creative thinking. Creating an effective solution requires understanding the end-users, as well as their problems, needs and experiences. That's why, during the empathize stage, we have created an empathy map of the end-users (the elderly and caregivers), that allowed us to gain knowledge about what the users do, say, think, and feel. The maps were built using knowledge gained through user interviews, listening to user stories, observations and immersion in a certain situation while present in the user's natural environment. All the activities were performed in a private elderly care center Nursing Home Idila Terzieva, in North Macedonia. In parallel to this, the requirement elicitation process was carried out, using semi-structured interviews, on-site visits and observations.

The information gathered at this stage, combined with documentation and detailed literature review, was used during the define stage, where the information was analyzed and synthetized in order to define the core problems. The 4 Ws technique was used to create a statement that outlines who has the problem, what that problem is, where they experience it, and why our solution should deliver a specific user experience to solve the user's problem.

The following problems concerning the elderly end-users group were identified: reaching fallen utensils from the floor, reaching some objects that are difficult to reach (ex: objects placed on the high shelf), detecting obstacles on the floor in order to prevent falls, keeping in touch with family and friends, reminding the elderly about: taking medications, medical appointments etc.

On the other side, main problems concerning caregivers were: substitute the caregiver in certain time-consuming situations (e.g. bringing tools and assets, beverages, etc.) in order to enable the caregivers to remain focused on more urgent situations, real-time visual and audio communication and consultation, and reminder.

With the knowledge gathered in the first two phases, we started the ideation (brainstorming) sessions in order to identify solutions to the problem. It took several ideation sessions to pinpoint and refine the ideas. As a result, at the end of this phase, it was decided that the robot should have manipulator capabilities, since the major part of the elderly were concerned about catching and carrying small objects that are hardly accessible for them. A telepresence system with a videoconferencing set, for a remote presence and interpersonal communication, was also rated as must-have functionality.

Over a period of several months, a design concept was formulated, which lead to the development of robot prototype, explained in detail in the following sub-sections.

2.2 Robot's structure

Figure 1 shows the developed telepresence robot, which is composed of a mobile robot base, robot body, robot arm and robot head.

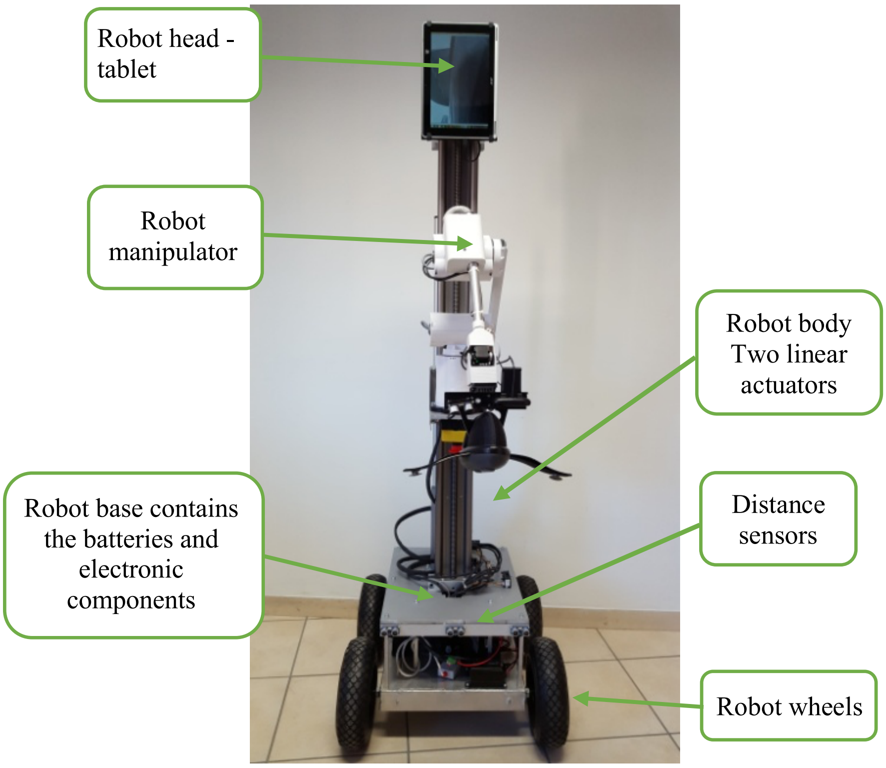

Figure 1: Developed assistive telepresence robot

2.2.1 Mobile base

For the mobile base, two gusset-like aluminum frames are used, which are rigidly connected to each other by means of eight laterally arranged aluminum supports. The spacing between the two frames is 10cm. This creates enough space for placing the electric components inside. Two 12V LiFePO4 (Li-ion) batteries with 20Ah are placed at the beck of the robot for stability. The position of all the components inside the base is carefully calculated in order to increase the stability of the entire robot system. Moreover, the robot is equipped with an array of 12 ultrasound sensors placed laterally.

The robot base also bears the linear actuators which are vertically positioned, and mimic the robot's body. For additional stability, the actuators are tightly coupled to the upper frame of the basis by a supportive triangular element made of gusseted aluminum with a thickness of 8mm.

2.2.2 Robot body

The robot body is composed of two linear actuators from IGUS that contain ball-bearing mounted trapezoidal threaded drive spindle. The actuators have a full length of 100cm. The motion is performed without any usage of lubricant, which makes the actuators clean and easy for maintenance.

The effective stroke of the actuators is limited to 80% of its full length due to safety reasons. The rest 20% of the stroke are defined as a dead zone. One of the actuators is used for vertical positioning of the robot arm and the other for positioning of the tablet (that mimics the robot head). The position of the actuators is independently controlled via the integrated linear encoders with a precision of 0.1mm.

2.2.3 Robot arm

For the arm, a serial six axis kinematic manipulator (Mover6) is used. The arm weighs 3.5kg, it has a reach of 600mm and could lift objects up to 600g. The accurate position control is achieved by using servo motors for all six joints of the arm, and encoders used by four of them. Considering the effective stroke of the actuator and the reach of the robot arm, the robot is capable to pick up objects from the floor as well as picking up objects from high shelfs up to 210cm. To enable precise gripping of objects, an ultrasound sensor and a web camera are placed near the gripper.

2.2.4 Robot head

The 10'' tablet mounted at the top end of the linear actuator act as a robot head, which is adjustable. It can be moved vertically using the linear actuator and it can be positioned from 60cm up to 180 cm from the ground. Moreover, the robot head can be paned (from -60° to +60°) and tilted (from -20° to +20°) by the means of two servo motors.

The tablet can be used during interpersonal communication with family members, friends or caregivers, who can virtually visit the elderly and interact with them in their living environment. The tablet camera can also be used during navigation task, for providing visual feedback to the operator.

2.2.5 Robot dimensions and weight

The physical dimensions of the entire robot system are 48cm × 52cm × 180cm (L×W×H). It weighs 42 kg and can reach a maximum movement speed of 2.2m/s. Robot's dimensions and its physical characteristics were motivated by the users' requirements as well as the intended application in indoor (home) environments.

3 Robot modelling and control

The developed wheeled robot platform is applying skid steering paradigm. Considering the skid steering model applied to four wheel electric vehicles derived in [Shuang, 2007] as well as the geometry of the developed mobile robot base (see Figure 2), the dynamic model of the base could be described with the following equations:

$$M\ddot{x} = \sum_{i=1}^{4} F_i \cos\phi - \sum_{i=1}^{4} S_i \sin\phi$$
$$M\ddot{y} = \sum_{i=1}^{4} F_i \sin\phi + \sum_{i=1}^{4} S_i \cos\phi$$
$$J\ddot{\phi} = (-F_1 + F_2 + F_3 - F_4)\frac{b}{2} + (S_1 + S_2)pa - (S_3 + S_4)(1-p)a \tag{1}$$

where M is the mass, J is the moment of inertia of the mobile robot, ϕ is the heading, v is the velocity, x and y are the rectangular position coordinates of the mobile robot. The dimensions of the mobile robot are captured with the length a and the width b.

Longitudinal tire forces due to slippage and lateral tire forces due to skid, for each wheel could be described with the following equations (indexes of the wheels are omitted for simplicity):

$$F = F_f \frac{v - v^F}{\sqrt{(v - v^F)^2 + (v^S)^2}}$$
$$S = -F_f \frac{v^S}{\sqrt{(v - v^F)^2 + (v^S)^2}} \tag{2}$$

where v^F and v^S are longitudinal and lateral speeds of the individual wheels, calculated with the following equations:

$$v_1{}^F = v_4{}^F = \dot{x}\cos\phi + \dot{y}\sin\phi - \frac{b}{2}\dot{\phi}$$
$$v_2{}^F = v_3{}^F = \dot{x}\cos\phi + \dot{y}\sin\phi + \frac{b}{2}\dot{\phi}$$
$$v_1{}^S = v_4{}^S = -\dot{x}\sin\phi + \dot{y}\cos\phi + pa\dot{\phi}$$
$$v_2{}^S = v_3{}^S = -\dot{x}\sin\phi + \dot{y}\cos\phi - (1-p)a\dot{\phi} \tag{3}$$

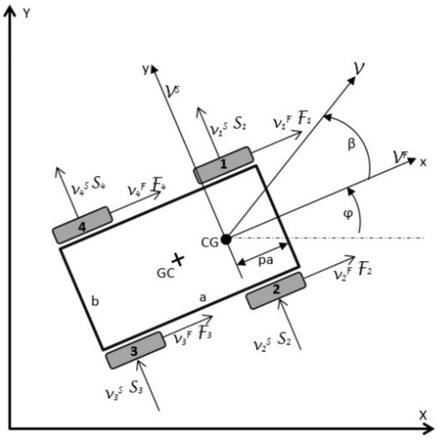

Figure 2: Geometrical model of the robot platform

The coefficient *p* varies between 0 and 1 and it defines the position of Center of Gravity (CG) with respect to the Geometrical Center (GC). F_f is the friction force which using the Columb model could be defined as:

$$F_f = \begin{cases} C\sqrt{(v - v^F)^2 + (v^S)^2} if \sqrt{(v - v^F)^2 + (v^S)^2} \leq \frac{\mu_0 Mg}{C} \\ \mu_0 Mg if \sqrt{(v - v^F)^2 + (v^S)^2} > \frac{\mu_0 Mg}{C} \end{cases} \tag{4}$$

where μ_0 is the friction coefficient and *C* is the stiffness of the tires.

From this model we can determine an implicit dependency of the local velocities and the heading during the skid steering and the input velocities.

However, as in other presented dynamic models in the literature [Tchoń, 2015] [Elshazly, 2014] [Wang, 2015] [Wu, 2015] [Kozłowski, 2004], it is still very specific because it is regarding the specific surface and tire model. On the other hand, odometry sensors, very often could not accurately track the robot's position due to the skidding and slippage. Therefore, Adaptive Neural Fuzzy Inference System (ANFIS) for the robot control was developed.

It combines positive characteristics from both fuzzy logic and neural networks under uncertainty and ambiguity circumstances, and they directly exploit expert knowledge bases [Huang, 2012]. It's fast learning and adaptation of back propagation capabilities enable to model and show very complex relationship between input and output data [Yildiz, 2009] as well as to fine tune fuzzy membership functions' parameters. Nowadays ANFIS are often used to support prediction tasks in various domains. In our case it is used to predict left and right wheel trains velocities.

The developed ANFIS follows the architecture originally proposed by Jang [Jang, 1993]. It is a network that consists of five layers (fuzzification layer, production layer, normalization layer, defuzzification layer, and output calculation layer). The nodes belonging to the same network layer perform the same function. The nodes are connected via synapses, and each synapse has a certain weight.

The network models the dependence of the velocities of the left and right wheel pairs on the distance to the obstacles, for the robot's left side (d_L), right side (d_R), front side (d_F), and rear side (d_B), as well as the heading angle error (h_{err}). The developed ANFIS with the same network structure is used in two parallel processes to calculate the velocities of the left and right wheel pairs.

Distances from the eventual obstacles in four main directions (left, right, front, and rear) are calculated as the minima of readings obtained by each sensor group (sensors positioned on the same side of the robot).

The network implements first-order Takagi–Sugeno-type model for the fuzzification and defuzzification phase. It contains a set of rules composed of 405 rules of the following type:

$$IF(d_L is A_i and d_R is B_j and d_F is C_k and d_B is D_l and h_{err} is E_m) THEN$$
$$fijklm = p_{ijklm}(d_L) + q_{ijklm}(d_R) + r_{ijklm}(d_F) + s_{ijklm}(d_B) + t_{ijklm}(h_{err}) + u_{ijklm} \quad (5)$$

where *A, B, C, D*, and *E* are the fuzzy membership sets for the variables d_L, d_R, d_F, d_B, and h_{err}, correspondingly, and *p, q, r, s, t*, and *u* are linear parameters (consequent parameters). They are identified in the forward pass using the method of least squares.

To optimize the ANFIS that contains a relatively big number of rules in the knowledge database, some modifications are necessary. Keeping in mind that many of the network paths have near-zero specific weights, the traditional ANFIS has been modified in a way that it fires (during computation and training) only for those network paths that have specific weights above a certain threshold. Moreover, the computation overload was significantly reduced by introducing linear membership functions instead of bell-shaped functions. The network was further optimized by not training the premise but only the consequence parameters, because they affect the output more strongly. The reduction in the network approximation capability introduced with the latest modification was compensated by introducing additional membership functions describing one of the input variables. Each of the network layers perform specific function.

The input layer collects input signals from proximity sensors indicating the distances to the nearest obstacle, as well as the difference between the current and the target heading angle.

The fuzzification layer is composed of adaptive nodes that calculate the fuzzy membership functions for the given inputs:

$$\begin{aligned}
O_{1,Ai} &= \mu_{Ai}(d_L), i = 1,2,3 \\
O_{1,Bj} &= \mu_{Bj}(d_R), j = 1,2,3 \\
O_{1,Ck} &= \mu_{Ck}(d_F), k = 1,2,3 \\
O_{1,Dl} &= \mu_{Dl}(d_B), l = 1,2,3 \\
O_{1,Em} &= \mu_{Em}(h_{err}), m = 1,2,3,4,5
\end{aligned} \quad (6)$$

where μ_{Ai}, μ_{Bj}, μ_{Ck}, μ_{Dl}, and μ_{Em} are the membership functions of the fuzzy sets and in our system, they are defined as linear functions (triangular and trapezoidal) (see Figure 3).

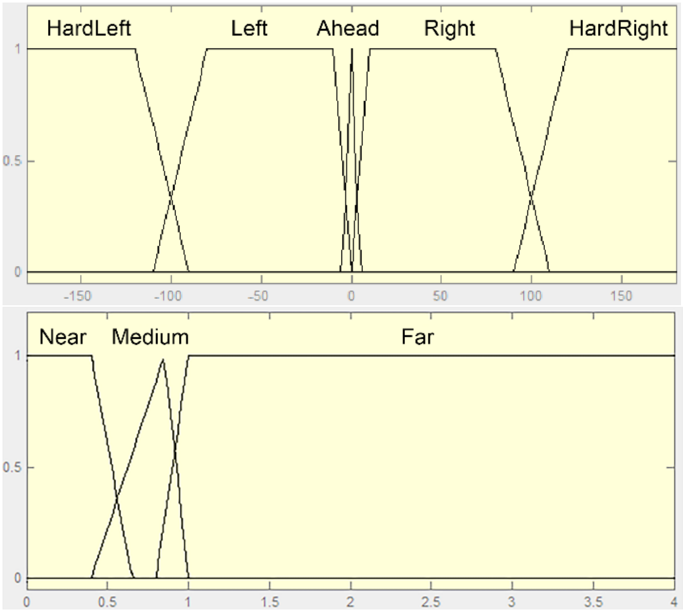

Figure 3: Membership functions for input parameters
(a) – variables d_L, d_R, d_F, d_B *and (b) – variable* h_{err} *of the controller*

Usually, each membership function is described parametrically, and their parameters are considered as premise parameters that are tuned during the process of training. In our case, they are fixed because of the above-discussed optimization reasons.

The production layer is composed of fixed nodes, each containing a simple function that calculates the firing strength of each fuzzy rule:

$$O_{2,ijklm} = \mu_{Ai}(d_L)\mu_{Bj}(d_R)\mu_{Ck}(d_F)\mu_{Dl}(d_B)\mu_{Em}(h_{err}) = w_{ijklm} \quad (7)$$

Here, i, j, k, l = 1, 2, 3; m = 1, 2, 3, 4, 5 and w_{ijklm} denotes the firing strength of the rule.

The normalization layer contains fixed nodes aimed at normalizing the firing strength according to the following rule:

$$O_{3,ijklm} = \overline{w}_{ijklm} = \frac{w_{ijklm}}{\sum_i \sum_j \sum_k \sum_l \sum_m w_{ijklm}} \quad (8)$$

Here, i, j, k, l = 1, 2, 3 and m = 1, 2, 3, 4, 5.

The defuzzification layer is composed of adaptive nodes, each implementing a function to calculate the consequence of the fuzzy rules:

$$O_{4,ijklm} = \overline{w}_{ijklm} f_{ijklm} = \overline{w}_{ijklm}(p_{ijklm}(d_L) + q_{ijklm}(d_R) + r_{ijklm}(d_F) + s_{ijklm}(d_B) + t_{ijklm}(h_{err}) + u_{ijklm}) \tag{9}$$

Here, i, j, k, l = 1, 2, 3 and m = 1, 2, 3, 4, 5.

The output calculation layer contains a single fixed node that calculates the inferred output, i.e., the speed of the wheels:

$$O_{5,1} = \sum_i \sum_j \sum_k \sum_l \sum_m \overline{w}_{ijklm} f_{ijklm} \tag{10}$$

3.1 Training of the controller

In order to achieve the optimal performance of the designed controller an appropriate training process should be conducted. The process of training aims at finding those values of the premise and consequent parameters, in the layers 1 and 4 correspondingly, that will minimize the error of the output parameter. In our case, we have used the hybrid learning methodology that applies the least-square algorithm in the process of optimization of the premise parameters while the gradient descent algorithm is applied to optimize the consequent parameters.

Having in mind the robot construction details (physical dimensions of its components, performances of the actuators, etc.) and based on the domain knowledge, the corresponding training dataset has been generated. To train the ANFIS controller, training dataset consisting of 450 tuples was used. Each tuple contained values for the input parameters (left, right, front and rare distances to the nearby objects) as well as heading angle error. Moreover, each tuple also contained the corresponding values for the left and right angular velocities. 80% of the tuples in this dataset were used for training while the others for evaluation.

The results after the training process showed that the controller can reach the average error for predicting the angular velocity of 0.1 rad/s after 147 epochs. The dependency of the average error on the epoch number is presented in Figure 4.

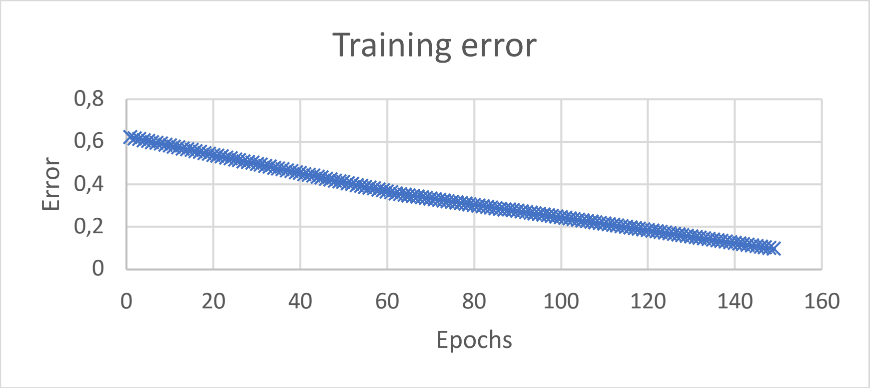

Figure 4: Relationship between training error and epoch’s number

3.2 Control software architecture

In order to provide a safe interaction with the robot, the developed control architecture is following the Model-View-Controller pattern [Koceski, 2016]. It permits reactive control, i.e., closed-control loop and autonomous behavior and safety management, even when the communication channel between the operator and the robot is interrupted (due to a network failure, for example).

This architecture supports two types of robot control - manual teleoperation and shared control paradigm. During the manual control the operator has full remote control of the robot, for the entire period of operation. In contrary, when the robot is operated using shared control the user gives the high-level instruction while the robot executes the low-level tasks autonomously [Koceska, 2019].

The user can give two types of instructions to the robot: (1) specification of a general direction of movement or destination; and (2) definition of an ordered sequence of pre-defined actions i.e. high-level primitives, such as: WallFollowing, TakeMedicineBox, DoorPasing, etc.

4 Evaluation study

Different scenarios were designed to test the developed assistive telepresence robot system from a socio-technical viewpoint. The technical implementation of the realized scenarios focused on robot’s functionalities, such as: robot navigation, obstacles detection and avoidance, robot manipulator and telepresence capabilities. The robot was tested in simulation and experimentally (in real environment).

In order to capture the experience of using the developed robot in daily tasks, a questionnaire was compiled and given to all participants at the end of the evaluation.

4.1 Participants

In order to evaluate the robot in real environment with the potential end-users, the experiments were conducted in a private elderly care center Nursing Home Idila Terzieva. 26 elderly persons (14 males and 12 females) and 5 professional caregivers, from this elderly care center, were involved in the experiments. Elderly were aged between 55-75 years (M=64), while the caregivers were aged between 35-49 years (M=40). All subjects gave their written consent for participation in the study. Participants had moderately-low technology experience, as shown through the technology experience questionnaire (SD=3.2), which was conducted before performing the experiments. Also, none of the participants had previous experience in robot manipulation and control.

4.2 Experiments

Several experiments were realized to test the functionalities of the developed robot.

The first experiment focused on software architecture. The idea was to compare the shared-control and manual control paradigm. This experiment consisted of two parts: the first one was realized in a simulated environment while the second one in a real environment. The navigation capabilities and obstacle avoidance were also tested during this experiment.

The second experiment aimed to test the robot manipulator, and its functionalities such as fetch and carry small objects.

The last experiment focused on interpersonal communication of the elderly with their caregivers.

4.3 Data collection

Individual user tests were conducted with the older adults and their caregivers. One evaluator was constantly present during the tests.

Before executing the experiments, the evaluator explained the robot working principle as well as the robot functionalities. Afterwards, participants were given the opportunity to practice each of the scenarios envisaged for the specified group of participants. During the practice session the participant was free to ask questions concerning the execution of the scenario.

After the completion of the training, the experiments started. The robot was operated with a remote control (i.e. tablet), using a specially designed touch screen interface [Koceski, 2016].

The final stage of the evaluation included filling out the questionnaires, in order to capture user's experience.

5 Simulation and experimental results

Experiment 1 - Considering the importance of the navigation and teleoperation abilities, the developed assistive telepresence robot was tested in simulation and experimentally. In the simulation, the gains for the kinematic controller were chosen to be $k\rho=3$, $k\alpha=8$, $k\beta=-1.5$ [Siegwart, 2011].

The robot speed was limited by to $vmax=1.5m/s$. The robot's initial heading was $\theta=0$ degrees. The developed control architecture and the robot capability of navigation while avoiding obstacles and corners as well as moving through corridors were evaluated in two different scenarios. For this purpose, two different experimental setups were created both in the physical as well as in the simulation environment. They are presented on Figure 5 and Figure6. The dimensions of these environments are expressed in meters. The simulation path from start (marked with red circle) to goal (marked with green circle) is depicted with red, while the path in the real-world experiment is depicted with blue color. In both environments ten runs were conducted using the shared-control paradigm. Only the professional caregivers were included in this experiment. Average lengths of the experimental and simulation paths are presented in Table1.

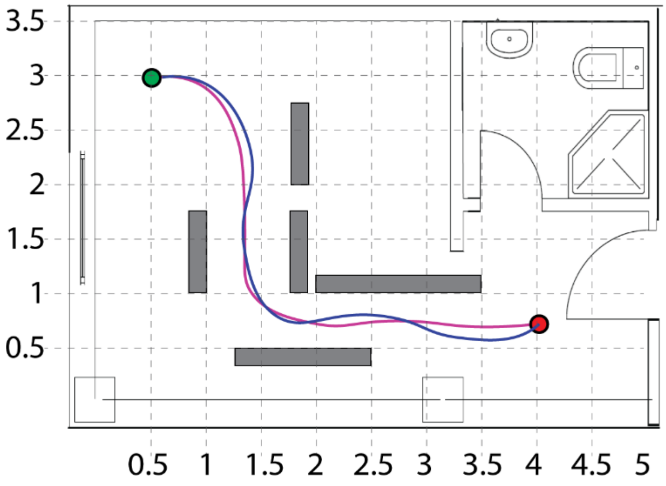

Figure 5: Navigation in corridor like environment

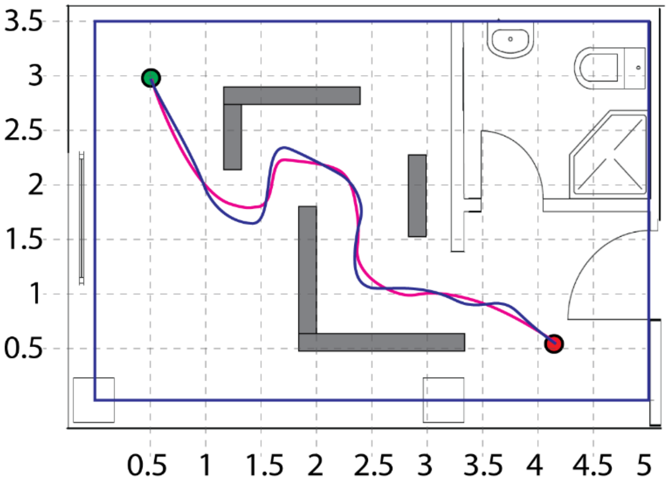

Figure 6: Corners avoidance in the environment

Environment #	**Path length (meters)**	
	Simulation	Experimental
1	4.73	4.82
2	5.03	5.15

Table 1: Lengths of the paths during the experiments and the simulation

In order to compare manual and shared-control algorithm the robot was placed in a real evaluation environment. Both elderly and caregivers were asked to navigate the robot avoiding the obstacles, intentionally placed on its way from Start to Finish (see Figure7).

They conducted two runs: one using the manual and the other using the shared-control algorithm. During each run collisions with the objects were counted, and times to finish the missions were recorded.

Figure 7: Evaluation environment for navigation scenario

Average number of collisions and running times for both modes are presented in Table 2.

Mode	**Elderly**		**Caregivers**	
	No. of collisions (St. Dev)	Running time (s) (St. Dev)	No. of collisions (St. Dev)	Running time (s) (St. Dev)
Manual	8.03 (1.49)	134.10 (16.12)	6.25 (1.17)	112.35 (10.26)
Shared control	3.85 (1.10)	110.25 (15.06)	2.44 (0.88)	92.30 (8.22)

Table 2: Comparison between two modes of control - mean value (standard deviation)

The presented results show that the implemented shared control mechanism helped the operators significantly reduce the collisions. For the elderly, these varies from 8.03 (SD=1.49) to 3.85 (SD=1.10) (a two-sample t-test also showed statistically significant difference between the two modes t(26)=7.18, *p*=0.001). For the caregivers, they varied from 6.25 (SD=1.17) to 2.44 (SD=0.88) (a two-sample t-test also showed statistically significant difference between the two modes t(5)=5.52, *p*=0.001).

As a result of collision reduction, the running time for each mission, was also reduced.

Experiment 2 - The robot manipulator was tested on fetch and carry tasks. Two scenarios were realized. In the first scenario, a cup of water placed on the table, located at one side of the room, was to be taken from a robot, positioned on the opposite side of the room. In particular, the scenario covers the following activities: move the robot from its starting position to the table, move the arm, move the gripper, grab the cup, pick up the cup, bring the cup to the user (see Figure 8).

Figure 8: Experimental environment (experiment 2)

In the second scenario robot manipulator was used for retrieving the dropped object (a box of medicine) from the floor. The scenario covers the following activities: position the robot near the dropped object, move the arm, move the gripper, grab the box, pick up the box, bring the box to the user.

The scenarios were completed with a success rate of 74% and 82%, respectively (which is very satisfactory). The rates are based on the robot grasping on the first attempt, in each trial (each participant performed two trials, for each scenario). Most of the failures were due to the inappropriate robot/arm positioning, which resulted in the inability of the manipulator to successfully grab the specified object.

The manipulator functionality was the most appreciated by the elderly, given the fact that there is a great risk of a fall when trying to reach an object that is set high, or when they bend trying to get the object dropped on the floor. They stated that the robot manipulator can help them to be more independent, since they won’t need a constant human presence, besides them.

Professional caregivers were also satisfied with this functionality, as it will reduce their time spent on assisting the elderly with simple tasks.

Experiment 3 - For testing the telepresence capabilities the following scenario was realized. The professional caregiver drives the robot and positions it in front of an elderly person with whom he/she wants to talk. The caregiver positions the tablet in order to be able to see the interlocutor. Then, he/she initiates a call, and the elderly response to the call.

The scenario was completed successfully by all participants. They judged positively both the video and audio communication, and stated that the interaction through the robot was very pleasant.

The elderly emphasized that the videoconference set will be particularly usable for interaction with the family members who live abroad and cannot visit them often. According to them, the robot’s physical presence mimics face-to-face interaction, so they prefer this type of communication over a telephone call or a regular video call. This view accords with Porges theory that highlights the importance of face-to-face interaction in maintaining social bonds and reducing the feeling of loneliness and social isolation [Porges, 2011]. Regarding the privacy issue, which is often raised when using telepresence systems, in this study, the older participants did not foresee any problems with the remote visits and surveillance. This attitude is probably due to the fact that they live in a nursing home where they are constantly monitored.

Professional caregivers also perceived the telepresence system as a tool that could improve their surveillance, allowing them to monitor the physical condition of the elderly and their daily activities. On the other hand, the system could help them manage their workload and time devoted to patients, thus improving the health care.

Questionnaire – In order to evaluate users’ experiences with the developed mobile telepresence robot system, a self-reported 18-item questionnaire was designed. The questions were divided into 5 topics: 1) Navigation 2) Manipulator use 3) Telepresence functionality 4) Remote control 5) Usefulness. Each reply was graded within a 5-point Likert scale ranging from “Strongly disagree” (1) through “Strongly agree” (5). The questions in each topic were selected in a way to reflect the user feedback related to the main functionalities of the robot, used in developed scenarios. This is also in line with the problems statement, determined during the define stage.

Questions, as well as responses of the participants, are shown in the following table (see Table 3).

Task	Question	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
Navigation	The speed at which the robot is moving is acceptable	20	8	2	1	0
	It was easy to move the robot in a straight line	18	9	2	2	0
	It was easy to make turns with the robot	8	16	1	4	2
	It was easy to navigate the robot around obstacles	7	11	2	8	3
Manipulator use	Positioning the robot arm was easy	8	10	8	4	1
	The use of the end effector for grasping the object was easy	9	12	6	4	1
	The moving speed of the manipulator is acceptable	17	7	6	1	0
	The way a robot uses its manipulator is pleasant.	17	12	1	1	0
	The speed at which the robot approached me, was appropriate.	19	8	3	1	0

Telepresence functionality	Using the telepresence functionality was pleasant.	20	8	3	0	0
	The picture and sound of a video-call were acceptable	18	8	5	0	0
	The position of tablet during the call was appropriate.	18	7	2	4	0
	The remote visits don't violate my privacy *	16	8	0	2	0
Remote control	Using the touch screen was pleasant.	10	12	4	4	1
	It was clear how to operate the robot using a remote control	9	10	7	2	3
Usefulness	The robot can assist me with some daily tasks, which I can't perform alone *	18	6	2	0	0
	The robot can help me to be more independent *	18	6	1	1	0
	The robot can act like an assistant of the caregiver **	4	1	0	0	0

Table 3: Number of participant response after performing the scenario.
** only for the elderly group. ** only for the caregiver group*

Overall, all participants had a positive experience with the robot and its performance (see Figure 9). The elderly persons found the robot very useful, especially in execution of tasks they cannot perform alone and for which they need assistance. They think that in this way they will be less dependent on caregivers, reducing the need for their constant presence. Professional caregivers also have positive opinions about the robot and its functionalities. They stated that the robot could alleviate their workload, since they have to take care of many elderly during the day. However, they all agree that the robot can assist them only with specific daily tasks. For some, human control and touch is still needed.

In average, questions from the Telepresence functionality topic have the highest score among all topics. Participants found the real-time communication using mobile robot more interesting and appealing than phone. The videoconference functionality was particularly significant to elderly, in order to avoid social isolation, and to be more often in communication with the family members who live abroad and cannot visit them often.

In the case of Remote control, questions have the lowest average score. Although patients are used to touch devices (some with difficulty), they found it difficult to use it in specific situations, because the touch screen did not have an optimal response to pulsations. This situation aroused frustration in some cases. It could also impact the perception of other robot functionalities, so it is one of the elements to be considered for future improvement.

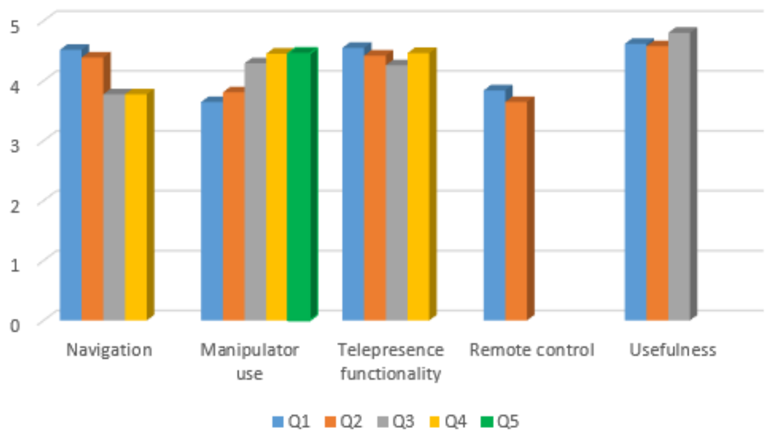

Figure 9: Participants' responses to the items on the questionnaire (the average of each question on the topic is presented.

Despite some reservation amongst caregivers about the presence of the robot in the elderly's environment, the questionnaire confirms the positive attitude of the elderly towards having a robot in their vicinity, which is in line with some other studies [Koceski, 2016] [Sung, 2007] [Boissy, 2007] [Sabelli, 2011] [Bedaf, 2018].

6 Conclusion

The paper presents the design and validation of a low cost assistive telepresence robot using Design Thinking methodology. The robot consists of a mobile robot base, a robot body, a robot arm and a robot head. Its human-like height together with a tablet mounted on top of the actuator, allows for natural eye contact and the virtual presence of a remote person in elderly's living environment. The developed robot is intended for social interaction, assistance of elderly and support of professional caregivers in providing better help care. The robot arm with the end-effector allows the robot to fetch and carry various objects. The telepresence functionality allows virtual visit by the caregivers, as well as social interaction with the elderly.

The developed robot was tested in simulation and experimentally. The experiments were conducted in real environment, with potential end users, which is a major advantage of this study. Several experiments were realized to test the control architecture and robot functionalities.

Simulation of the robot in the navigation task showed the effectiveness of the chosen control algorithm. The simulation was performed before the real time implementation of the algorithm, since it presents an inexpensive and very reliable approach of analysis of algorithms.

The experimental results with the end users, showed satisfactory results. It was shown that operators have significantly fewer hits and need less time to complete the task when using the shared-control mode. The manipulator was considered as very useful functionality, although some participants found it difficult to use it. This is not surprising, given the fact that the participants did not have much time to practice. However, they all have a positive opinion about using the manipulator functionality in the future. The possibility of using telepresence capabilities and video call, was also positively accepted by all participants.

Overall, all participants showed a positive attitude towards the developed robot. The robot's usefulness was also rated very highly, which encourages us, given the fact that this is considered one of the main reasons for using the robot system.

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APPENDIX A

1. Technical characteristics of the individual robot elements

Individual robot element	Technical characteristics	No.of units
Gusset aluminum frames	Thickness - 8mm; Spacing between the frames -10cm;	2
Pneumatic wheel	Diameter -10-inch; Solid steel axles diameter- 1/2-inch; Double ball bearing support.	4
Planetary gear DC motor	Reduction ration - 10:15; Rated torque - 30 kgf-cm; Rated speed - 252rpm;	4
Roboteq SDC2130 controller	Convert commands received from microcomputer into high voltage and high current output for driving one or two DC motors; Compact board – 70x70; Number of channels – 2; Command modes - RS232, USB.	1
LiFePO4 battery	12V Li-ion battery with 20Ah	2
Linear actuator (IGUS)	Full length - 100cm.	2
Stepper Motor Nema23XL	Driven by the 2MA860H driver.	1
Robot arm Mover6	Serial six axis kinematic manipulator Weigh - 3.5kg; Reach - 600mm; Gripper – classic two finger gripper; magnetic gripper.	1

2. Power supply system configuration

2.1 Mobile base power supply

Two HQ BAT-LEAD-12 lead acid batteries with 12V and 10Ah (fitted on the back side of the mobile base and connected serially) supply unregulated power which is afterwards scaled and distributed to the various components and subsystem.

2.2. Robot body and robot arm power supply

Modified and calibrated HQ-CONV.DC10A DC-DC convertor is used for:

- scaling down the voltage to 5V to power up the USB Hub to which various sensors are connected;
- scaling down the voltage to 7V to power up the ArduinoMega Board;
- scaling down the voltage to 12V to power up the Mover6 robot arm.

2.3 Robot head power supply

The 10” tablet (that mimic the robot head) has a battery life of up to 8 hours and is therefore treated as an independent system. It has been empirically validated that even during high performance computing operations the tablet independence is exceeding 3 hours, which is above the robot batteries’ life expectancy.

2.4 Robot power utilization

Considering the designed power supply configuration, the power utilization in the worst case scenario has been calculated and given in the following table.
The batteries’ life expectancy, according to the worst case power consumption of various subsystems, is calculated to be around 1.27h (20Ah / 15.7A).

Component	**Voltage (V)**	**Current (A)**	**Power (W)**
Motors and Roboteq driver	24	2.1*4=8.4	201.6
Stepper Motor Nema23XL	24	4.2	100.8
Arduino	7	0.2	1.4
Ultra Sound HC-SR04	5	0.015 * 10=0.15	0.75
Robot arm Mover6	12	2.5	30
Camera	5	0.250	1.25

Table 4: Robot power utilization

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