Development of a Model & Control strategy for Telepresence Mobile Robot

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Abstract— **This paper aimed at the design of an Omni-wheeled Mobile Robot for Telepresence Purpose. Where "Telepresence Robot" is a social robot, mainly used to allow the end users to stay connected to the mobile robot and communicating audio-visual data. By which the end user controls the movement of the Robot from a remote place through WIFI. Our new product design and development showed a better performance than the existing products in the market like VGO and Double. We focused on achieving an easy and smooth manoeuvrability of the system with in small area, controllability, user interface (which is made to be adjustable from 85 cm to 185 cm) and robustness/stability. We start off from the kinematic analysis and following the dynamic analysis, considering some simplifications for ease of our analysis. The robot base design includes a 3D CAD model for each part or machine elements and components and a 3D assembly of our Model, which includes 3 Omni directional wheels actuated by 3 DC Motors and 1 Stepper Motor for the user interface with adjustable height using simple screw and nut mechanism and an Apple Mobile. In this paper the control is done with the LQR feedback control systems strategy and the DC Motors are controlled using the output voltage from the Arduino controller based on the need of appropriate speed and direction set forth by the operator. We employed a closed loop PID controller with a wheel encoder as a feedback sensor. The choice of the wheels, motors, user interface, electronics and communication units with additional smart material selection are wise so that it results in an optimal design and with maximum satisfaction to the user requirements, which are discussed and predefined as a target to our QFD (Quality Functional Deployment) Analysis.**

***Index Terms*—Control, Omni-wheel, Telepresence Social robot, QFD**

I. INTRODUCTION

A mobile robot is a machine controlled by software that use sensors and other technology to identify its surroundings and move around its environment. Mobile robots function using a combination of artificial intelligence (AI) and physical robotic elements, such as wheels, tracks and legs. Telepresence refers to a set of technologies which allow a person to feel as if they were present, to give the appearance of being present, or to have an effect, via telerobotics, at a place other than their true location.

A popular application is found in telepresence videoconferencing, the highest possible level of videotelephony. Telepresence via video deploys greater technical sophistication and improved fidelity of both sight and sound than in traditional videoconferencing. Technical advancements in mobile collaboration have also extended the capabilities of videoconferencing beyond the boardroom for use with hand-held mobile devices, enabling collaboration independent of location. Some study shows that assistive technology in general, telepresence and assistance robots have a high potential to play a role in eldercare in the near future, by improving the quality of eldercare, providing services that are beyond human staff capabilities [1].

A telepresence robot is a device that allows people to participate in video conferences on a moveable platform from a remote location.

The users can remotely control the robot's motion and interact with each other through a video screen. Such systems, which were originally designed to promote social interaction between people, have become popular in various application areas such as office environments, health care, independent living for the elderly, and distance learning [2].

Telepresence systems allow a human operator to control and navigate a mobile robot around the remote environment and interact with their audiences through video conferencing. Telepresence robots suffer significant challenges during navigation due to communication time delays, and there exists a great variety of ways to move across a solid surface by mobile robots. The most important are wheels, tracks and legs [3] [4]. Wheels are the most used since they offer simpler mechanics and construction easiness. Legs and tracks require complex mechanics and heavier hardware for the same payload, but these have the advantage of running across uneven surfaces

II. MATERIALS AND METHODS

As this paper reports a new teleprescence robot design, by which the end user controls the movement from a remote place through WIFI, we focused on achieving an easy and smooth maneuverability of the system and within small area.

Furthermore, we started off from the kinematics analysis, following the dynamics analysis considering some simplifications. We also assumed the robot movement is only limited to that of flat surfaces. The robot base design includes three omni directional wheels actuated by Dc motors and height adjustable user interface. Then the control is done with the LQR feedback control systems strategy.

III. CUSTOMER REQUIREMENTS

Table 1: Customer Requirements

Requirement	Note	Rank
Handling/Maneuverability		4
Controllable		3
Easy to control at low speed		2
Carry User interface at 1m		2
Robust		2
Compact		2
Autonomy		1
Dynamic performance		4
Layout two wheels or more		0
Baseline electronics		3

Maneuverability

Maneuverability is the primarily needed for indoor mobile robot, due to compact environment. Omni wheels are the best choices as they can roll freely in two directions. It can roll like a normal wheel or roll laterally using the wheels along its circumference.

Omni-directional wheels allow a robot to convert from a nonholonomic robot to a holonomic robot. The robot can move sideways which make it faster and more efficient in reaching its given goal and it is highly maneuverable. Our robot consisting of three Omni wheels represent the omnidirectional mobile robot with mobility of three and steeribility of zero.

Controllable

The controllability of the robot is affected by the wheel slip, since we neglected the wheel slip in the formulation of the kinematics and dynamics, the system rely on feedback systems and sensors like wheel encoders and Hall Effect sensor built in inside the DC motors. The model based controller used to reduce the effect of external disturbance and wheel slip based on the error detected using the feedback control system. Precise tracking of the reference motor shaft speed can be achieved using the controllers.

User interface

The user interface is made to be adjusted from 82cm to 125cm so that it would be easy to use it for sitting or standing person. The height adjustment is controlled by Screw and bolt mechanism coupled on stepper motor. The stepper motor is chosen for high precision and high torque performance.

Robust/stable

Our design use feedback controller systems to make the robot resistant for external disturbance. The robot body design also help to keep stability by concentrating all the masses on the robot center of mass. Vibration and falling of the robot are reduced by reducing the mass of the stand (for the interface) using appropriate material selection.

Baseline Electronics

Adafruit motor shield connected to the Arduino is used to control the robot base movement, height adjustment. The motor driver is compact with the ability to drive all the 3 Dc motors, a stepper motor. The user interface use Wi-Fi connection to communicate with the robot operator. Streaming video, audio signals sent and received using a tablet running an android firmware. Robot control signal from the tablet then sent to the arduino using serial connection. NiCd battery with voltage regulators is used to supply power to the electronics.

IV. Benchmarks

We considered two telepresence robot systems available on the market, VGO and double, and compared with our new design as depicted in Table 2.

The most popular mobile robot, double, has features of variable height, compact size with two wheels and easy to use but it is a little bit costly than the others. Its two wheels make it unstable, hence with lower controllability. The VGO has four wheels which reduces its maneuverability and compactness, and positively affects its stability and robustness. Our custom mobile robot satisfies customer requirements better, by 88 % while VGO and double show only 80 %. Ease to maneuver, variable height, stable and robust on flat surfaces characterizes the system.

Table 2: Benchmarking of two existing products with the new design

■ VGO ● Double ▲ Our Design

Requirement	1	2	3	4	5
Handling /Maneuverability			■	●	▲
Controllable			●	▲ ■	
Easy to control at low speed				● ▲ ■	
Carry User interface at 1m				■	▲ ●
Robust			●	■ ▲	
Compact			■	▲	●
Autonomy			●	■	
Dynamic performance				▲ ■ ●	
Layout two wheels or more					● ▲ ■
Baseline electronics				●	■ ▲

V. Technical Specifications

Customer requirements led to those technical specifications as depicted in Table 3 below, which are the major parameters for the new design. Dimension takes the highest score, so that we should focus on the number of wheels and motors; size of camera, display and battery. This enables to satisfy requirements maneuverability, compactness and layout of wheels. Speed, related to controllability and dynamic performance, is achieved by a wise choice of motor and control system. We also tried to fulfill the remaining requirements.

Table 3: Technical Specifications

Technical specifications	Unit	Rank
Height	Cm	38
Weight	Kg	58
Velocity Range	m/s	88
Dimension	Cm^2	92
Battery life	Hrs.	55
Communication latency	sec	42

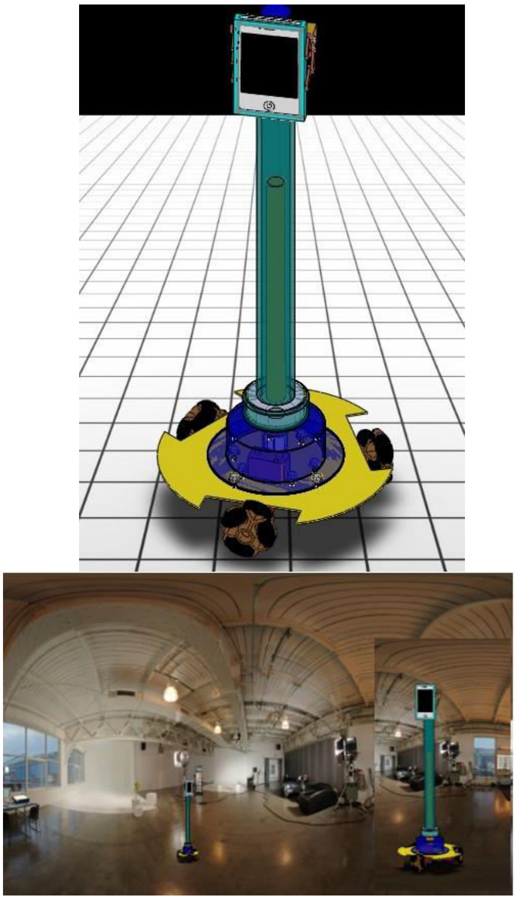

Figure 1: Final representation of our 3D mobile robot model & simulation using Solidworks

VI. Targets/Goals and Parameters

We gathered some data on the values of technical parameters for VGO and double and considering our customer requirements, a range of values of those parameters for our custom design are derived.

Table 4: Target Values

Technical specifications	Unit	Min Value	Max Value
Height	m	0.7	1.80
Weight	Kg	8	20
Velocity Range	m/s	0.5	2
Dimension(Diameter)	Cm^2	24X80	30X180
Battery life	Hrs	6	12
Communication latency	sec	0.5	2

VII. System Models and Solutions

In this section, the robot equations of motion are derived based on some typical simplifying assumptions. For simplicity of the analysis, the mass of the robot is assumed to be distributed uniformly, so the center of mass is contained within the geometrical vertical axis of the robot. It is assumed that the wheels have no slippage in the direction of traction force. The wheel contact friction forces that are not in the direction of traction force are neglected. The motor electrical time constant is also neglected.

A. *Kinematics*

There are two coordinate frames used in the modeling: the body frame and the world frame. The body frame is fixed on the moving robot with the origin in the robot geometric center, which is assumed to be the center of gravity, the world frame is fixed on the field of robot movement, as depicted in Fig 2 below. Each wheel, separated by 120 degree, has its own reference frame on which it rotates.

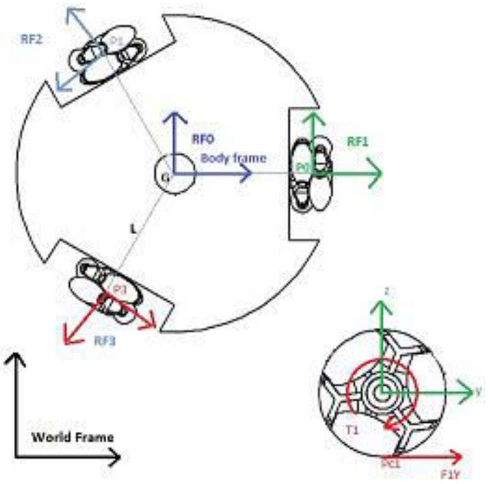

Figure 2: Coordinates & Forces

MBsymba code used to formulate the coordinates is as follows:

RF0:= translate(X (t), Y (t), 0).rotate ('Z', theta (t)):

RF1:= RF0.translate (L, 0, 0).rotate ('X', Phi1 (t)):

RF2:=RF0.rotate ('Z', sigma1).translate (L, 0, 0).rotate ('X', Phi2 (t)):

RF3:= RF0.rotate ('Z', sigma2).translate (L, 0, 0).rotate ('X', Phi3 (t)):

Symbols used in the robot kinematic and dynamic model are listed in the nomenclature below.

Body frame

Vx Vy Velocity component of body frame fy

Traction forces of each wheel (N)

$\dot{\emptyset}$ Motor shaft speed (rad/s)

World frame

(X, Y) Robot location

Θ Robot Orientation angle (rad)

Mechanical Constants

Mb Robot mass (Kg)

Ib Robot moment of inertia (Kgm2)

R Wheel radius

L Radius of the robot body

σ Wheel orientation angle(deg)

The Omni-wheel has freely rotating rollers at the periphery and the axis of rotation of the rollers are at an angle to the axis of rotation of the wheel. Thus, they have two degrees of freedom as opposed to conventional wheels which have one degree of freedom. To ensure that the wheel always has two degrees of freedom, we consider a wheel having two layers of rollers as shown in Fig below.

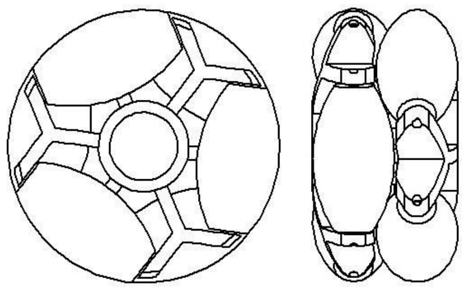

Figure 3: Omni wheels layout

Since the rollers have unconstrained motion we only consider the wheel to get the kinematics of the system. Hence considering the constraint equation due to non-slipping of the wheel in the direction of rotation, we can formulate the kinematics as in (1). From the kinematics model of the robot, it is clear that the wheel velocity is a function of linear and angular velocities of robot center of mass, i.e.

$$\begin{vmatrix} \dot{\emptyset} \\ \dot{\emptyset} \\ \dot{\emptyset} \end{vmatrix} = \frac{1}{R} \begin{vmatrix} 0 & 1 & L \\ \frac{\sqrt{3}}{2} & \frac{1}{2} & L \\ \frac{\sqrt{3}}{2} & \frac{1}{2} & L \end{vmatrix} \begin{vmatrix} V_x \\ V_y \\ \theta \end{vmatrix} = [K] \begin{vmatrix} V_x \\ V_y \\ \theta \end{vmatrix} \quad (1)$$

Where, the [K] matrix relates $\dot{\emptyset}$ and V is analogous to Jacobian matrix.

B. *Dynamics*

The kinetic energy of the robot is given by the wheel rotational energy, and the robot translational and rotational energies. The kinetic energy contribution of the barrels on the Omni-wheel are neglected. The Lagrangian for the robot is given as in (2).

$$l = \frac{1}{2}\{M_b V^2{}_x + M_b V^2{}_y + I_b \dot{\theta}^2 + \sum I_{wi} \dot{\varphi}^2{}_i\} \quad (2)$$

Using the Lagrangian formulation, we can derive the Equations of motion for robot systems as in (3)

$$\frac{d}{dt}\left\{\frac{\partial}{\partial q_j}\right\} - \frac{\partial}{\partial q_j} = f_j \ \ ,j = 1..6 \quad (3)$$

Where, L, is the Lagrangian of the robot given in (2), qi =1...6 is the set {X, Y, θ,∅1,∅2,∅3} of generalized coordinates, and f are the generalized forces. Hence the six generalized forces can be written as in (4)

$$F = \left\{ R[K]^T \begin{vmatrix} fy1 \\ fy2 \\ fy3 \end{vmatrix} \ and \ \begin{vmatrix} T1 - fy1 \\ T2 - fy2 \\ T3 - fy3 \end{vmatrix} \right\} \quad (4)$$

The dynamic equations of motion for the Robot, excluding the effects of wheel slip, can be written as by combining (3) & (4) as in (5)

$$\begin{vmatrix} M_b & 0 & 0 \\ 0 & M_b & 0 \\ 0 & 0 & I_b \end{vmatrix} \begin{vmatrix} \dot{V}_x \\ \dot{V}_y \\ \dot{\theta} \end{vmatrix} = R[K]^T \begin{vmatrix} fy1 \\ fy2 \\ fy3 \end{vmatrix}$$

$$\begin{vmatrix} I_{w1} & 0 & 0 \\ 0 & I_{w2} & 0 \\ 0 & 0 & I_{w3} \end{vmatrix} \begin{vmatrix} \ddot{\varphi}_1 \\ \ddot{\varphi}_2 \\ \ddot{\varphi}_3 \end{vmatrix} - R \begin{vmatrix} fy1 \\ fy2 \\ fy3 \end{vmatrix} = \begin{vmatrix} T1 \\ T2 \\ T3 \end{vmatrix} \quad (5)$$

We can make the following observations from the dynamic equations of motion.

1) The individual wheel dynamics are coupled with the robot dynamics through the tractive forces.
2) The only input to this model of the robot are the wheel torques.

The robot nonlinear dynamics can be reduced to a linear system if either the robot does not rotate while in translation, or the robot rotates at a fixed position without translation.

C. DC motor Dynamics

The dynamics of each DC motor are described using the following equations in (6)

$$L_a \frac{di_a}{dt} + R_a I_a + K_3 \omega_m = E$$

$$R_a \dot{\omega}_m + b_0 \omega_m + \frac{Rf}{n} = K_2 I_a \quad (6)$$

Where E is the applied armature voltage, Ia is the armature current, La is the armature inductance, Ra is the armature resistance, K3 is the back emf constant, K2 is the motor torque constant, J0 is the combined inertia of the motor, gear train and wheel referred to the motor shaft, b0 is the viscous-friction coefficient of the motor, gear and wheel combination and n is the motor to wheel gear ratio. Since the electrical time constant of the motor is very small compared to the mechanical time constant, we can neglect the motor electric circuit dynamics, which leads to the equation in (7)

$$L \frac{di_a}{dt} = 0 \ , \ I_a = \frac{1}{R_a}(E - K_3 \omega_m) \quad (7)$$

With this assumption, and using vector notation, the dynamics of the three identical motors can be written.

VIII. CONTROL STRATEGIES

The six state variables we are interested in controlling are: (x, y) the position of the robot with respect to the inertial reference, (x ˙,y ˙) is the velocity of the robot with respect to the field plane, θ is the angular position and θ ˙ is the angular velocity, so it is sufficient to use them to describe the state of the robot.

the robot equations of motion are derived based on some typical simplifying assumptions. For simplicity of the analysis, the mass of the robot is assumed to be distributed uniformly, so the center of mass is contained within the geometrical vertical axis of the robot.

Since the angular position θ is one of the state variables this implies that the model in is non-linear, and that represents an important difficulty for the purpose of controlling the robot. This is why it became necessary to find a way to linearize the model. Angle θ has a non-linear effect on the dynamics of state variables because as the robot rotates also the driving forces, which are the control variables. After linearization we can realize the state space model of the linearized dynamics.

The state space matrix using the 6 states and motor torques as inputs are defined as follows. Matrix A simply expresses the relationships among the six state variables, and is given as in (8)

$$A=\begin{bmatrix} 0_{3x3} & I_{3x3} \\ 0_{3x3} & 0_{3x3} \end{bmatrix} \tag{8}$$

Matrix B expresses the correct influence of each torque over the respective acceleration only for the case in which the angular position θ of the robot is zero, and is given as in (9)

$$B=\begin{bmatrix} 0_{3x3} \\ B1_{3x3} \end{bmatrix} \tag{9}$$

B1 contain values which are function of Mb, Ib, R and inertia of each wheel. Since the robot is controlled remotely by a user LQR control approach is used rather than other linear state-feedback controller design techniques. In LQR, the solution strikes a balance between the transient behavior of the state variables and the energy consumed by the actuators. The resulting poles are implicitly determined by the choice of matrices Q and R, rather than being explicitly specified, so that we would be able to assign the weight of the control problem for each states using the program used by the user.

LQR control problem consists on finding the state-feedback matrix K such that U = −Kx minimizes the performance index J given as in (10).

$$J=\int_0^{\infty} (X^T QX + U^T RU)dt \tag{10}$$

Subjected to the dynamics of the robot given by equation (3 & 4).The performance index J specifies the total cost of the control strategy, which depends on an integral quadratic measure of the state x and control u. Q and R represent positive definite matrices that give a weighted measure of the cost of each state variable and control variable, respectively.

For simplicity, in our solution Q and R, are defined to be diagonal matrices in (11)

$$Q=\begin{bmatrix} C_{xy} & 0 & 0 & 0 & 0 & 0 \\ 0 & C_{xy} & 0 & 0 & 0 & 0 \\ 0 & 0 & C_\theta & 0 & 0 & 0 \\ 0 & 0 & 0 & C_v & 0 & 0 \\ 0 & 0 & 0 & 0 & C_v & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{\dot\theta} \end{bmatrix}$$

$$R=\begin{bmatrix} C_m & 0 & 0 \\ 0 & C_m & 0 \\ 0 & 0 & C_m \end{bmatrix} \tag{11}$$

Where,

- Cxy: cost weight of the XY position of the robot
- Cv: cost weight of the XY speed of the robot
- Cθ: cost weight of the angular position of the robot
- Cθ ̇: cost weight of the angular speed of the robot
- Cm: cost weight of the torque of the driving motors

This set of cost weights has to be specified intelligently by the program for each of the segments of the robot movement. The weights specify the relative cost of each variable, and by an appropriate choice of their values, the user program easily adjust the optimality index for different control strategies. For example, if Cm is very large in comparison to the other weights then our strategy will be to save energy, if Cxy is large in comparison to the rest then the strategy dictates that the robot should reach the target region as soon as possible without regard to a specific target final speed, angle or energy consumption.

After specifying Q, R for an optimum cost function we can get the state feedback gain K for the given A, B matrix. In the mean while we have to check meeting the transient response specifications and the magnitude constraint on the state and the control inputs.
A Matlab simulation is done to get the optimal feedback gain of the closed loop system, and the step response of the system. We control the DC Motors, using the output voltage from the Arduino controller based on the wanted speed and direction by the operator. We used a closed loop PID controller with a wheel encoder as a feedback sensor.

DC Motor Model

$$\dot{X} = Ax + Bu$$
$$Y = Cx$$

The following step was the verification of the controllability of the system. The reachability matrix had full rank, so the system was controllable and we could stabilize it using the LQR control.

We choose the following matrix to minimize the quality function of the LQR:

$$R = [1.7], Q = \begin{bmatrix} 0.4 & 0 \\ 0 & 0.4 \end{bmatrix}$$

The resulting system is the following:

$$A = \begin{bmatrix} 0 & 1 \\ -0.64 & -1.30 \end{bmatrix}, B = \begin{bmatrix} 0 \\ -1.32 \end{bmatrix},$$

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, D = 0$$

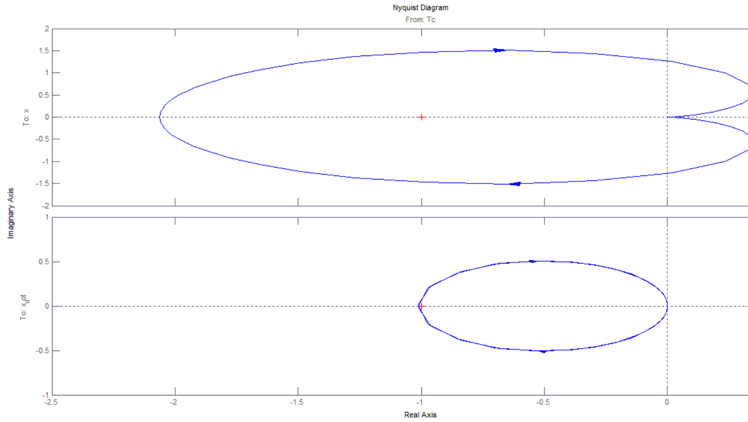

Figure 4: Nyquist diagrams for the controlled system

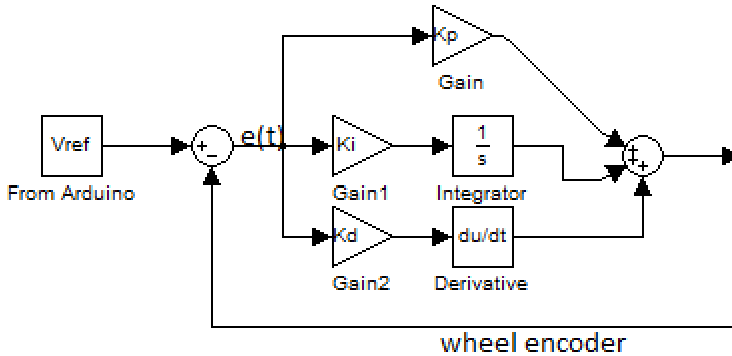

Figure 5: PID control schematic of one motor

The step response of the system for different values of Kp, KI, & KD

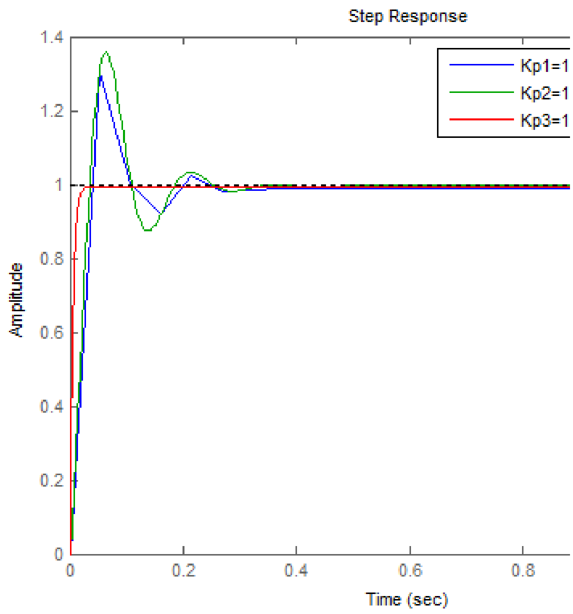

Figure 6: Step response

IX. RESULT DISCUSSIONS

After all the design phases are done, we got the following values for each of the design parameters as depicted in Table 5 below. We successfully obtained better results than the ones planned, which satisfy all the customer's requirements. This result shows that, with a LQR controller, our system is stable and can follow an acceleration profile.

Table 5: Design specs

Technical specifications	Unit	Actual value
Height	m	0.825-1.15
Weight	*Kg*	11
Velocity Range	m/s	0.5-1.75
Dimension(diameter)	m^2	0.25X1.25
Battery life	Hrs	10
Communication latency	sec	1.5

X. CONCLUSIONS

Telepresence robots are aimed to allow the end- users to stay connected to the mobile robot and communicating audio-visual data. Our new design showed better performances than VGO and Double. The choice of wheels, motors, user interface, electronics and communication units are wise such that it results in optimal design and with maximum satisfaction of user requirements.

As our new mobile robot movement is limited to flat surfaces, the main limitation of this project was that we didn't have considered the third dimension, so to have completely neglected the steering phase of the system. A further model improvement could be the studying of this phase to allow the robot move on a plane and not only along a straight line. Another assumption was the hypothesis of full state access. Even this simplification is not too restrictive, because with an appropriate sensors fusion it is possible to know all the state values. Another detail that we have neglected is the software running on the tablet, to complete the design we should write its characteristic and the I/O needed. A possible improvement is the implementation of a hybrid control that could switch between different velocity profiles, depending on the inclination of the floor and the distance that have to be covered.

Furthermore, its performance can be improved by adding tilt sensors, gyroscopes, accelerometers obstacle sensors and incorporating additional stabilizing codes.

APPENDIX

Electrical Components and power analysis

Motors: three DC motors are used to drive the three omni-directional wheels; one stepper motor, to vary the height of the robot and two servo motors, for the pan-tilt movement of the camera.

1. **Dc Motor**: The tables below show the specifications of each of the DC motors:

Parameters	Value	Unit
Rated voltage	12	Volt
Rated torque	1.5	Kg/cm
Rated current	530	mA
Minimum shaft	1.5	rpm

speed		
Maximum shaft speed	200	rpm
Rated output	4.22	w

2. **Stepper Motor**:
- NEMA 34 Bipolar high torque stepper motor
- Weight -640 oz.
- Hybrid Motor 1.8°/200 steps per rev.
- 4.5A Amps Current per Phase

Figure 7: DC motor and Stepper motor used

3. **Controller**: An on board Arduino, with a motor shield is used as a controller platform for our robotic system. It provides a shield to powers up all the motors and electronics of the system; drives the motors using the L293D H-bridge chipset which provides 0.6A per bridge (1.2A peak); controls the whole performance and communication of the system by ATMEGA328P microcontroller.

Figure 8: Arduino Duemilanove with Adafruit motor shield

4. **Display**: an LCD display with 1.44'' screen is used. It has smaller dimension when compared to the two model.

5. **Battery**: - 12 V 1000 mAh NiCd battery pack for robots made with 8xAA, 1000mAh TENERGY high power NiCd Batteries. Delivers long run time with powerful performance with Standard Tamiya Connector.
- Voltage: 12V - Battery: NiCd
- Connector Type: Standard Tamiya.
- Dimensions: Height 0.5"; Width 2.3"; Length 3.9"
- Weight: 8 Oz.

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