Design of a Fault-Tolerant Holonomic Mobile Platform

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ABSTRACT

The mobile platform described in this paper is a holonomic type robotic vehicle. It is designed for use as a slave system in the development of a fault-tolerant teleoperation test-bed system. Therefore, the vehicle itself has a fault-tolerant design. This paper reviews the previous designs of mobile platforms, introduces several conceptual designs and the final design. Initial component selection is also presented and mobile platform motion planning is described.

Keywords

Mobile, Platform, Fault-tolerant, Omni-directional, Teleoperation

1. INTRODUCTION

Today many different robotic systems are utilized in various applications. These systems can be branched into two groups as fixed and mobile systems. Fixed systems are widely used in industry in which tasks are repeated tasks and do not require mobility. Robotic arms and Cartesian assembly robots are examples of these systems. Mobility is often required in field exploration or transportation tasks. Robots travel either in the air, on the ground or under the sea to accomplish these tasks.

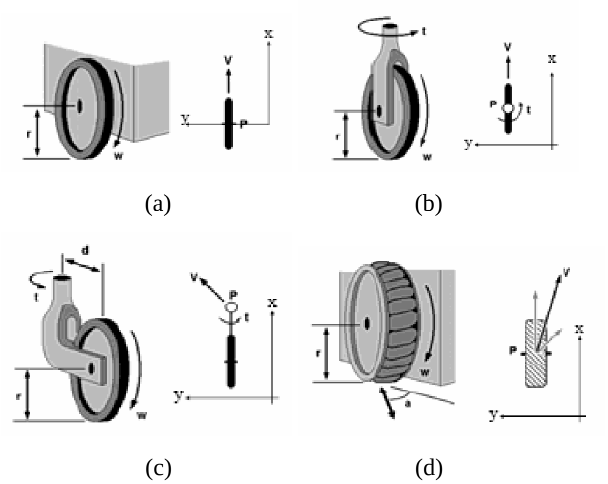
Robots that are in motion on the ground (mobile platforms) can be divided into two main groups as legged and wheeled platforms. In this study, we focus on wheeled platforms and specifically holonomic (omni-directional) type mobile robots. Omni-directional wheels are used to develop a holonomic mobile robot. These wheels enable the robot to move in any direction at any orientation. There is no need to change the orientation of the platform while traveling in an arbitrary trajectory. The direction of the linear velocity is independent from the orientation of the vehicle. Ultimately, the system developed is a three degree-of-freedom planar robot. The mobile platform to be developed will be used in a teleoperation application. Teleoperation is a robotics application that involves two robotic systems. These systems are called master and slave. Master system is often a joystick controlled by the operator in order to drive the slave system. Slave system is the robot working at a distant or hazardous environment. In our studies our master system is a two degree-of-freedom, uncoupled, gimbal-based joystick. The mobile platform to be built will be used as the slave system of this teleoperation test-bed.

In most of the teleoperation applications, the slave robot is at a distant or hazardous site that is unreachable by the humans conveniently or safely. Some teleoperation tasks are also very crucial and have to be accomplished even if the slave system has a faulty element. This is the main reason that fault tolerance is a requirement for most of the teleoperation systems. Teleoperation system considered in this study is designed to have fault-tolerant architecture. Slave subsystem is not an exception to this and will be designed to have fault tolerance in link level and also will have Triple Modular Redundancy (TMR) for sensor configuration. Link level redundancy will be provided using four independently actuated wheels for a three degree-of-freedom motion.

This paper first reviews available literature on mobile platforms, specifically on holonomic systems. In the following section, design concepts developed in this work are presented and the selection of the final design is discussed by providing the details of the design. Component selection section describes the parts selected and their specifications. Later, the following section explains the motion of the platform during its regular motion and also when a motor fails to operate. Finally, conclusions are given and future work is addressed in the last section.

2. BACKGROUND

Mobile robots are either legged, wheeled or a combination of these two. Various types of wheels are found in the literature. Some of these wheels are called fixed wheel, centered orientable, off-centered orientable (caster), and omni-directional (Swedish) wheel.



(a) (b)

(c) (d)

Figure 1. (a) Fixed (b) centered orientable, (c) off-centered orientable, (d) omni-directional wheel

Omni-directional wheel is mostly used to build a holonomic type mobile platform. These platforms move in any direction at any orientation. Their orientation can also be changed without affecting the linear motion. This way motion along all three degrees of freedom of the mobile platform can be achieved independently.

There are also different types of omni-directional wheels. West and Asada [1] developed a ball wheel mechanism. In the ball wheel design, power from a motor is transmitted through gears to an active roller ring and then to the ball via friction between the rollers and the ball as shown in the figure below.

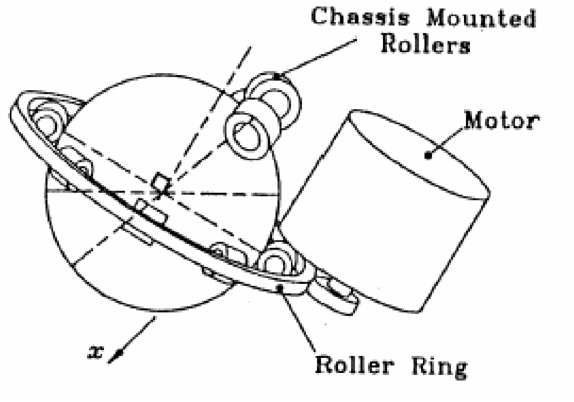


Figure 2. Ball wheel mechanism [1]

Kornylak Corporation has two types of omni-directional wheels listed at their website [2]. Ohio University used the Transwheel® of Kornylak Corp. for their omni-directional RoboCup players and goalkeeper [3, 4].

(a) (b)

Figure 3. (a) Transwheel®, (b) Omniwheel of Kornylak Corp.

North American Roller Products (NARP) [5] is also a producer of omni-directional wheels in different sizes and materials. They call their omni-directional wheels “All-side Rollers.”

Figure 4. All-side Roller of North American Roller Products

Researchers at Carnegie Mellon University built the Uranus mobile robot in early 90’s to provide a general-purpose mobile base to support research in indoor robot navigation [6]. Uranus had four traditional Swedish (Mecanum) wheels. Although the locations of the wheels are in customary formation for four-wheeled vehicles, the unique design of the Swedish wheels enabled the platform to move independently in all three degrees of freedom.

Figure 5. CMU’s Uranus [6]

Three actuated omni-directional wheels are enough to develop a holonomic vehicle that moves independently in all three degrees of freedom. Carnegie Mellon University later commercialised a new design of the holonomic mobile platform named Palm Pilot Robotic Kit (PPRK) [7]. In this new design three omni-directional wheels from North American Roller Products are used in a triangular configuration.

Figure 6. CMU’s PPRK [7]

Omni-directional mobile platforms became very popular in RoboCup (robot soccer games) since 2000. Universities built their players using omni-directional wheels in order to develop a holonomic mobile platform. This is mainly because they are more maneuverable, able to navigate tight quarters, and are easier to control. Ohio University and Padova University developed two different types of omni-directional mobile platforms for RoboCup. The first type is developed to be a regular player in the robot soccer game and had same wheel configuration as PPRK [3]. The second type was developed to be goalkeeper [4]. Goalkeeper was designed to have redundancy so it will have a better mobility, specifically to be able to go sideways easily. Cornell University also used four omni-directional wheeled platform for their RoboCup player design [8].

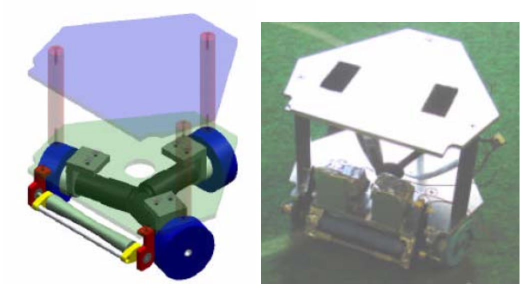


Figure 7. Ohio University RoboCup player [3]

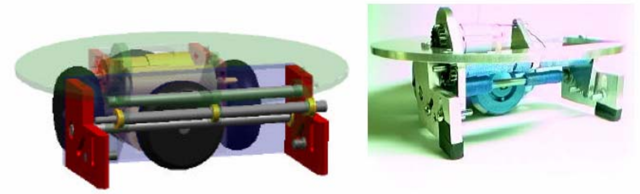


Figure 8. Ohio University RoboCup goalkeeper [4]

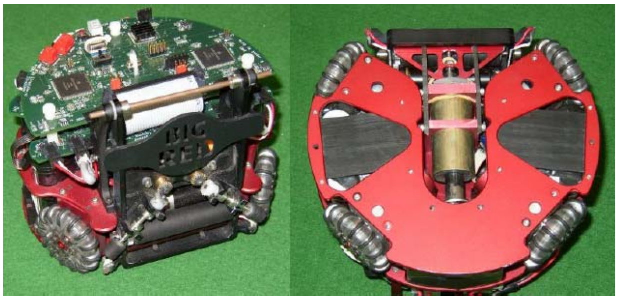


Figure 9. Cornell University RoboCup goalkeeper [8]

West and Asada used four of their ball wheel mechanisms to develop an omni-directional base of a wheelchair [9]. The vehicle had four independent servomotors driving the four ball wheels that allow the vehicle to move in an arbitrary direction from an arbitrary configuration as well as to change the angle between the two beams and thereby change the footprint. They had three objectives for having the control of the beam angle. One is to augment static stability by varying the footprint so that the mass centroid of the vehicle may be kept within the footprint at all times. The second is to reduce the width of the vehicle when going through a narrow doorway. The third is to change the gear ratio relating the vehicle speed to individual actuator speeds.

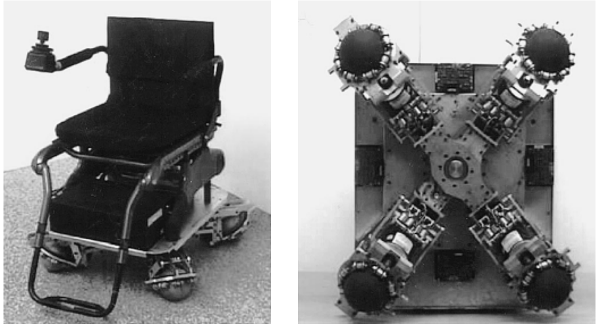


Figure 10. Reconfigurable omni-directional mobile platform [9]

Some researchers chose to work with caster wheels instead of omni-directional wheels to develop holonomic mobile platforms. Yu, Spenko, and Dubowsky developed SmartWalker using two active split offset casters (ASOC) and a conventional caster [10].

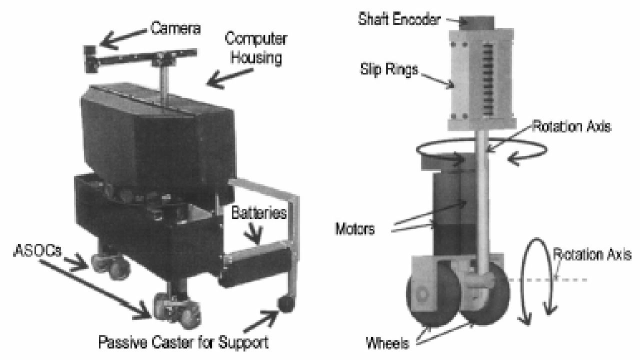


Figure 11. SmartWalker and its active split offset caster [10]

Holmberg and Khatib were also interested in using powered (active) castor mobile platforms to develop a holonomic vehicle. In their research, they used Nomadic XR4000 mobile platform with four powered caster wheels [11].

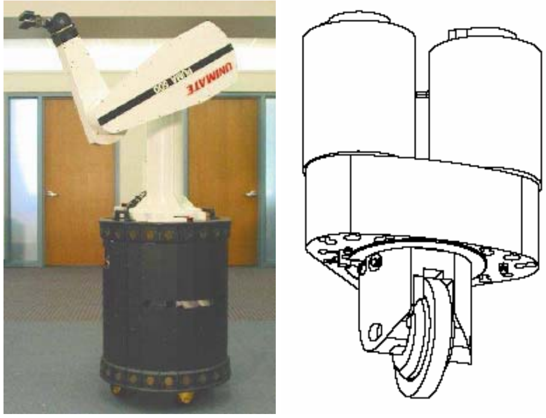


Figure 12. Nomadic XR4000 and its powered caster model [11]

3. DESIGN PROCESS

3.1 Design Criteria

The mobile platform to be designed will be used as a slave system in a teleoperation test-bed. Therefore, the platform will not be an autonomous vehicle, but will be driven by the commands sent from the master system. It should also feedback sensory information to the master system. The master system is a two degree-of-freedom joystick. The degrees-of-freedom of the joystick are uncoupled due to its unique gimbal design. An extra uncoupled degree-of-freedom can also be added to the joystick for future studies. Hence, the platform to be designed should have three degrees-of-freedom to be compatible with the joystick and preferably they should be uncoupled.

Another feature of the teleoperation system is that its subsystems should have fault tolerance. Slave system, which is the mobile platform, is no exception to this and it should have fault-tolerance. Since the robot to be designed is a mobile platform, it shouldn't have cables connected to the PC to have a larger workspace. Hence, the desired features for the mobile platform to be built are listed below:

- Three uncoupled degrees of freedom
- Sense the environment that it is working on
- Receive information from the master system
- Send information to the master system
- Cable-free communication with the master system
- Fault-tolerant design

3.2 Conceptual Designs

In the design process of the mobile platform, four design concepts are considered as briefly described below.

3.2.1 Design Concept 1

The first design concept is a two-wheel rear-end drive with Ackerman steering system. This design is mostly used in automobile industry. Fault tolerance could be achieved by changing the design so that reserve servomotors would be active to drive the wheels when there is a faulty servomotor. Its specifications are as follows:

Drive type: Two-wheel rear drive with Ackerman steering system

Total number of servos: 2

Degree-of-mobility: 1

Mobility: Travels in any direction by changing its orientation using the Ackerman steering system

Fault-tolerant design: Possible at the joint level

This vehicle supports a fixed arc motion, which means that it has only one instantaneous center of rotation (ICR). Therefore, it has one degree of mobility.

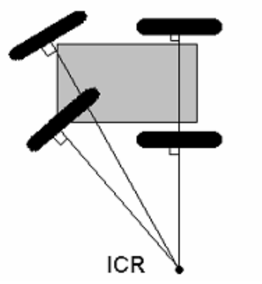


Figure 13. Two-wheel differential drive system [12]

3.2.2 Design Concept 2

The second design concept is a two-wheeled differential drive system in which a third point of contact by a roller-ball could be used for balance. Fault tolerance could be achieved by changing the design so that reserve servomotors would be active to drive the wheels when there is a faulty servomotor. Its specifications are as follows:

Drive type: Two-wheel differential

Total number of servos: 2

Degree of mobility: 2

Mobility: Travels in any direction by changing its orientation. It can also rotate about its wheels' midpoint

Fault-tolerant design: Possible in joint level

This vehicle has a variable arc motion, which means that it has a line of ICRs. Therefore, it has two degrees of mobility.

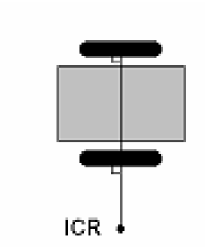


Figure 14. Two-wheel differential drive system [12]

3.2.3 Design Concept 3

The third design concept is a three omni-directional wheel drive system. This design is widely used in RoboCup players for the past 6 years. It is a holonomic vehicle by design. Fault tolerance could be achieved by changing the design so that reserve servomotors would be active to drive the wheels when there is a faulty servomotor. Its specifications are as follows:

Drive type: Three omni-directional wheel drive system

Total number of servos: 3

Degree-of-mobility: 3

Mobility: Travels in any direction at any orientation

Fault-tolerant design: Possible at the joint level

This vehicle has fully free motion, which means that ICRs can be located at any position. Therefore, it has three degrees of mobility.

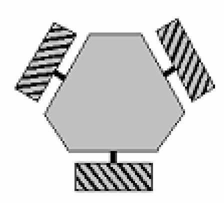


Figure 15. Three omni-directional wheel drive system [12]

3.2.4 Design Concept 4

The fourth design concept is a four omni-directional wheel drive system. This design is very similar to the design concept three, but it is redundant at the link level. It is a holonomic fault-tolerant vehicle by design. Its specifications are as follows:

Drive type: Four omni-directional wheel drive system

Total number of servos: 4

Degree-of-mobility: 3

Mobility: Travels in any direction at any orientation

Fault-tolerant design: Link level fault tolerance by design

This vehicle has fully free planar motion, which means that ICRs can be located at any position. Therefore, it has three degrees of mobility. Even if one of the wheels fails, the vehicle will still have three degrees of mobility.

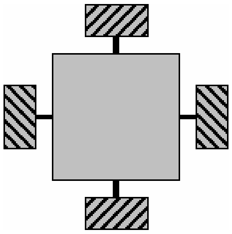


Figure 16. Four omni-directional wheel redundant drive system

3.3 Final Design

All the design concepts presented above can be built to exchange information with the master system via cable-free communication while gathering information about the environment using sensors. Mobile platform is to have three uncoupled degrees-of-freedom or in other words, it should have three degrees-of-mobility as stated in the design criteria. Differential drive system and Ackerman steering system are eliminated due to this factor. Omni-directional wheel drive systems still remain as a possible candidate since they both have three degrees-of-mobility.

Fault tolerance can be achieved for the three omni-directional wheel drive by having reserve actuators for each wheel actuator. This is a solution at the joint level fault tolerance. The shortcomings of this solution are that the design requires a total of six servos and the design becomes more complex.

Four omni-directional drive system has already a fault tolerance by design at the link level. Therefore, fault tolerance is achieved by only using four servos in the design. Taking these observations into account, among the four conceptual designs, four omni-directional wheel drive system is selected as the final design as it captures all the design specifications.

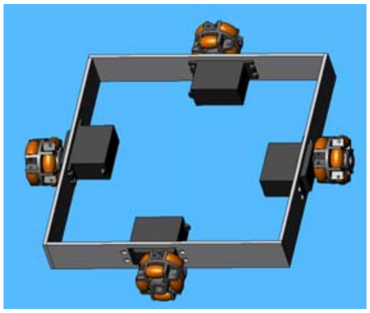


Figure 17. Final drive system design

Other than the mobility and fault tolerance requirements, another feature that is required from the slave system is to sense the environment that it is working on. Hence, the mobile platform should have sensors mounted onboard. Since this is a vehicle that navigates, it should have range sensors on all four sides. These sensors could be ultrasonic range sensors, infrared range sensors and laser range sensor. Fault tolerance can also be employed at the sensor configuration. Triple Modular Redundancy (TRI) [13] can be used not only for processors but also for sensors. Hence, three sensors can be placed on each side to form a triple voting configuration for the same sensory information. This means that a total of 12 sensors (3 sensors on each side x 4 sides) are to be used for the platform.

The control board for the platform should control at least four continuous-rotation R/C servomotors and should have at least twelve inputs with A/D converters to receive the sensory information. Control board should be able to communicate with the master system in a cable-free fashion. Since Bluetooth connection for wireless communication has become an accepted standard, the control board should also have a USB or RS-232 port for Bluetooth device connection.

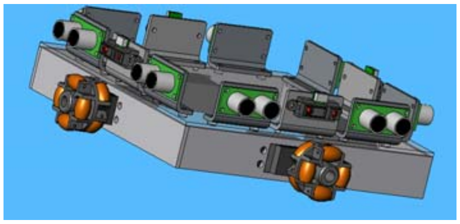


Figure 18. Final drive system design with sensor configuration

Servomotors selected should be velocity controlled since the master system of teleoperation sends velocity signals to control the mobile platform.

4. COMPONENT SELECTION

Parts to be used for the mobile platform construction are specified in the Final Design Section. These parts are omni-directional wheels, range sensors, continuos rotation R/C servomotors, control board, side and top brackets, and Bluetooth device for wireless communication.

4.1 Omni-directional Wheel Selection

There are two general types of commercially available omni-directional wheels in the market. First one is the Kornlylak Corp.'s "Transwheel$^{®}$" as shown in the Background Section. Kornylak Corp.'s "Omniwheel" and NARP's "All-side Roller" has the same design. "Omniwheel" and "All-side Roller" have a more sophisticated design to ensure the smoothness of the motion. Considering this, "Omniwheel" or "All-side Roller" is selected as the omni-directional wheel.

4.2 Range Sensor Selection

Possible range sensors for this size of mobile platform and its application should have good accuracy within one foot and should be reasonably priced with regard to the other parts of the system. There are two types sensors available that meet these requirements; one is the Infrared range sensor (IRS) and the other one is the Ultrasonic range sensor (URS). Different brands and types of these are available in the market in various price groups.

A combination of these sensors can also be used on the mobile platform. A total of twelve range sensors are to be used for fault-tolerant design. For instance, eight of them can be selected as one type and the remaining four can be selected another type of range sensors.

Figure 19. URS and IRS [14]

4.3 Servomotor Selection

Continuous rotation R/C servos are available in various specifications of torque and energy consumption. Probably Futaba® and Hitec are the most well-known producers of these servomotors. These servomotors are mostly velocity controlled which meets the specifications of the teleoperation.

Figure 20. Hitec [15] and Futaba [16] continuous rotation servomotors

4.4 Control Board Selection

Possible control boards that are commercially available are reduced to three after examining their specifications with the specification denoted in the Final Design Section. The first board is Pontech's SV203 board with 8 servomotor outputs and 5 inputs with 8-bit A/D converters. It has a serial port output for PC connection, which can also be connected to a Bluetooth device. Although the board meets the connection and servomotor port number specifications and it is fairly priced ($60), it doesn't have enough analog inputs for the twelve sensors. Three of these should be used at the same time to meet the specifications, which increase the board price to $180.

Figure 21. Pontech's SV203 control board [17]

The second board is the ServoPod™ from NewMicros. NewMicros has two versions of the board as serial port ($200) and USB ($250) connection boards. Both versions have 26 servomotor ports and 16 inputs with 12-bit A/D converters, which is more than enough for mobile platform specifications.

The last board is the Servio of Picobotics. This card has also a serial port for PC connection. It also has 20 servomotor ports and 8 inputs with 10-bit A/D converters. Although number of inputs does not meet the specification, the board is cheaper with respect to ServoPod™ and two of Servio boards can be used at the same time to meet the specifications. Using two Servio boards costs $140, which is a cost-effective solution for the board selection.

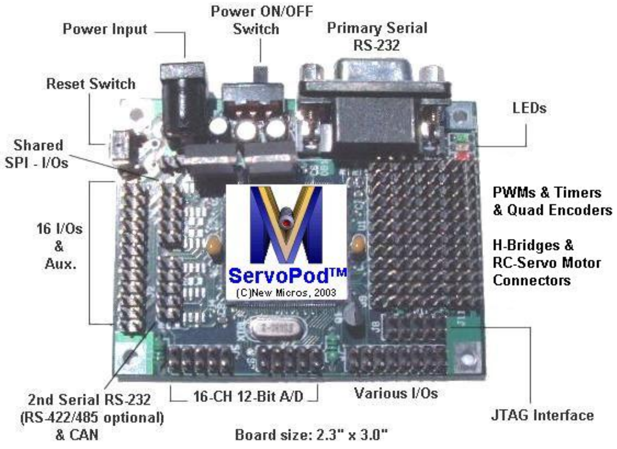


Figure 22. NewMicros' ServoPod™ control board [18]

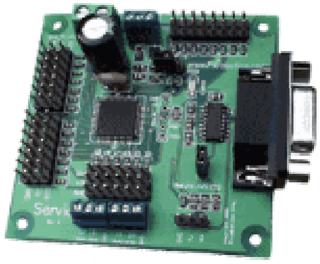


Figure 23. Picobotics' Servio control board [19]

4.5 Side and Top Brackets

Brackets are designed using SolidWorks. Three-mm aluminium sheets will be used to manufacture the side brackets. Plexiglass material will be used to manufacture the top bracket to better visualise the cable connections.

4.6 Serial Port Bluetooth Device Selection

Although there are many producers of USB connection Bluetooth devices, RS-232 serial port connection Bluetooth device producers are limited. Gridconnect's BluePort was found to be most cost-effective. It can transfer data from 9600 to 115200 Baud Rates and its range is 330 feet. When two Blue Port devices with the same Baud Rate are used at both ends (PC side and Control Board side), they are automatically connected without any need for software or driver instalment.

Figure 24. Gridconnect's BluePort couple [20]

4.7 Cost Estimate

Configuration of the sensors is selected to be eight of URS and four of IRS as described above. The most cost-effective selection is made for the rest of the parts that have two or more possible selections.

Table 1. Cost estimate of the mobile platform

Item	Unit Price	Quantity	Cost
Wheels	\$12	4	\$48
URS	\$25	8	\$200
IRS	\$12	4	\$48
Servomotor	\$7	4	\$28
Servio	\$70	2	\$140
BluePort	\$80	2	\$160
Misc.	\$20	1	\$20
Total			\$644

5. MOTION PLANNING

Servomotors have closed-loop velocity control of their own. PPRK of CMU is operated with three standard servomotors. Therefore, it can be assumed that these servomotors have enough power to operate the vehicle, and calculation of the actuator dynamics is not necessary. No slip model is considered for simplification purposes since the platform is a small one and the manipulation will be at relatively low speeds.

The mobile platform has three degrees of mobility whereas the master system (joystick) to drive the platform has only two degrees of freedom. One of the degrees of mobility of the platform will not be used when operated with the joystick. Joystick has its motions about the x- and y-axes as shown in Figure 25. These motions are uncoupled and identical about their own axis of rotation. Therefore, motions along the x and y directions are selected to be controlled for the mobile platform. Using two degrees of mobility simplifies the platform model since the orientation of the platform will not change.

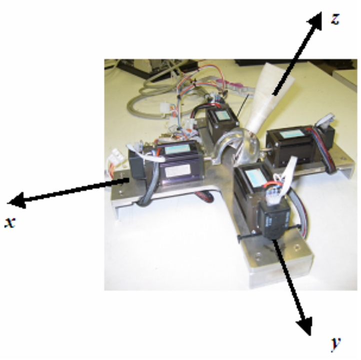


Figure 25. Master joystick configuration

5.1 Regular Motion Planning

The motion of the vehicle will be along the x and y directions and the orientation must not change during these motions. When all four wheels are actuated, the orientation (ω_v = 0) of the vehicle should not change. The figure below shows traction force (T_i) components and link lengths of the platform.

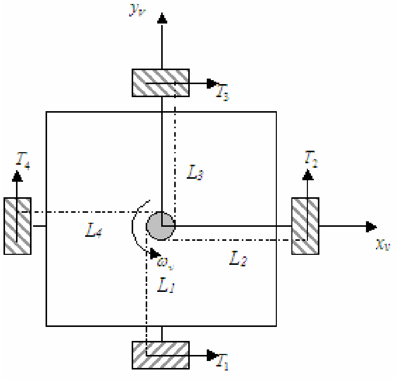


Figure 26. Mobile platform kinematics for regular motion

The platform is designed so that every wheel is at the same distance from the center of gravity of the vehicle.

$$L_1 = L_2 = L_3 = L_4 \tag{1}$$

Therefore, same traction force should be applied to parallel wheels during the motion not to change the orientation of the vehicle.

$$T_1 = T_3 \; ; \; T_2 = T_4 \tag{2}$$

If the applied traction force of one parallel wheel set are not equal to each other, compensation with the other wheel set can be accomplished using the equation below:

$$T_1 - T_3 = T_4 - T_2 \tag{3}$$

5.2 Three-Wheel Motion Planning

The mobile platform is designed redundant at the link level. There is one redundant wheel for a three degree-of-mobility motion. This is done so as to achieve fault tolerance. When one of the wheels fails, the other three wheels should be able to accomplish the task. Having redundancy enables this since only three wheels are necessary for the motion. Nevertheless, there should be a modification to the regular motion planning. The failing wheel now acts as a pivot point when the parallel wheel is actuated as shown in Figure 27.

Since the failing wheel acts as a pivot point, the angular rotation about the pivot (ω_P) should be kept zero in order to keep the orientation still. Therefore, when the parallel wheel of the failing wheel is active, traction forces should be set as:

$$2T_4 = T_1 - T_3 \tag{4}$$

As long as the equality in equation 4 is maintained, motions along the x and y-axes can be achieved without any change in the orientation of the platform.

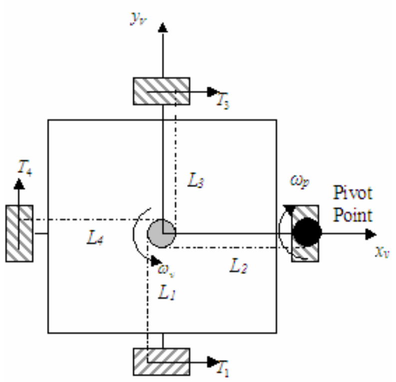


Figure 27. Mobile platform kinematics for three-wheel motion

6. CONCLUSION AND FUTURE WORK

A new concept of fault tolerance is addressed for holonomic mobile platforms. Four omni-directional wheeled (redundant) platforms have already been developed. Probably this paper is the first to employ fault tolerance using the redundancy of four wheels.

Future works involve fine design and construction of the platform. The next step is to test the fault-tolerant manipulation. Finally, this platform will be integrated into the fault-tolerant teleoperation test system for the performance evaluation of the developed teleoperation control techniques.

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