A Mobile Mechatronic Platform Architecture for Flexible Materials Handling

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Abstract

Mass production of customised products requires materials handling platform architectures to be flexible enough to accommodate varying geometries, masses and volumes of materials. Multi-agent control and coordination structures are under development to provide flexible and scalable transportation systems. In this paper the concept of Mechatronics has been used to develop a Flexible Materials Handling mobile platform architecture, suited to operation in both singular mobile platform and multiple cooperating mobile platform contexts. Materials handling was provided by the cooperation of multiple differential drive platforms fitted with servo operated and articulated conveyors.

1 Introduction

Mass production of customised products requires materials handling systems which are flexible and responsive enough to accommodate real-time changes in materials handling tasks. Flexible Materials Handling (FMH) systems require mobile platform architectures which are capable of functioning in singular context and in the context of multiple cooperating mobile platforms.

This requirement is important in the context of materials handling in manufacturing systems mass producing custom products. In these maufacturing environments, materials handling task instances can frequently vary between single mobile platform context and multiple cooperating mobile platform context. The mobile platforms should be able to associate and dissociate with one another accordingly.

Current AGV systems are designed to operate in singular context which limits the range of materials transportable to the set contained in the capabilities of a single vehicles material handling infrastructure. A move towards the utilisation of multiple cooperating AGV systems could greatly expand system scope. Control system and data fusion architectures are under development to aid in producing next generation AGV systems [Bostelman *et al.*, 2006]. The authors gather information on requested functionalities based on surveys performed on AGV manufacturers in the USA. In a final report based on a project in the Intelligent Manufacturing Systems (IMS) program, the characteristics which a materials handling system should posses in order to meet the requirements imposed by modern manufacturing systems are discussed. The system is defined as a Metamorphic Materials Handling System (MMHS). [MMHS-Metamorphic Materials Handling System - Final Report. 2003].

Research has been aimed at developing a Flexible Materials Handling (FMH) mobile platform architecture.

The objectives of the research were to:

- Develop a viable mobile platform architecture which can operate effectively in singular context or during multi-platform cooperation tasks.
- Integrate software and communication mechanisms on top of the mobile platforms which would allow for generic message passing primitives over a network system.

1.1 A Preliminary Insight

Omnidirectional wheels provide mobile robot bases with holonomic kinematics which allows for smoother material transportation in manufacturing environments with limited space.

Similar kinematics have been realised via the use of articulated manipulators fitted on nonholonomic differential drive mobile bases. These kinematic structures have been encapsulated in motion controllers. [Bhatt *et al.* 2004a, b]. When two such equipped mobile bases are attached to a common payload, Figure. 1., they have the capability to project lesser constrained kinematics onto the payload allowing for more accommodating motions around the working environment. The composite system has closed loop kinematic constraints however which must be considered when designing motion control primitives. From multi-platform cooperation in this manner it is apparent that.

- Nonholonomic mobile platforms can, via cooperation and articulation, impose lesser constrained kinematics on to their payloads.

Figure. 1. is a functional outlay of the mobile platform architecture used in this research depicting the degrees of freedom of the mobile bases and conveyor systems as well as a cooperation task instance.

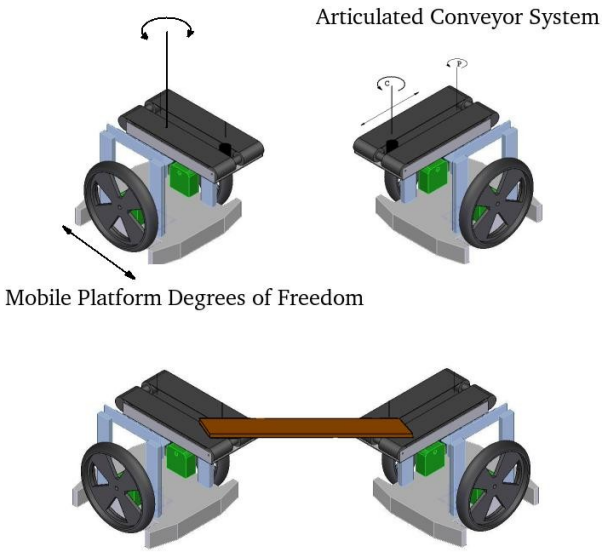

Figure. 1. Diagram of functional layout of nonholonomic mobile bases under cooperative task instance.

Each individual mobile platform consists of a differential drive system stabilised by two ball transfer units. Utilising ball transfer units lessens the constraints on manoeuvrability imposed by regular caster wheels [Abou-Samah, M. and Krovi, V. 2001].

2 The Mechatronics Approach

2.1 Mechatronics and System Integration

Mechtronics as a discipline is aimed at understanding how system performance and optimality is affected by the configurations and interconnections of various system constituents and sub-systems. This orientation to engineering systems design can aid in developing lean robust systems by placing emphasis on integration.

2.2 Flexible Materials Handling Environments

The manufacturing systems of the future may have vastly different layout configurations compared to current layouts which would perhaps accommodate the increase in autonomous elements in the manufacturing environment.

Figure. 2. depicts an outlay of a manufacturing system configured for FMH. The mobile materials handling platforms occupy three functionally separated areas. The three functional areas are the unprocessed material transport area, inter-machine tool material transportation and finished product retrieval and dispatch.

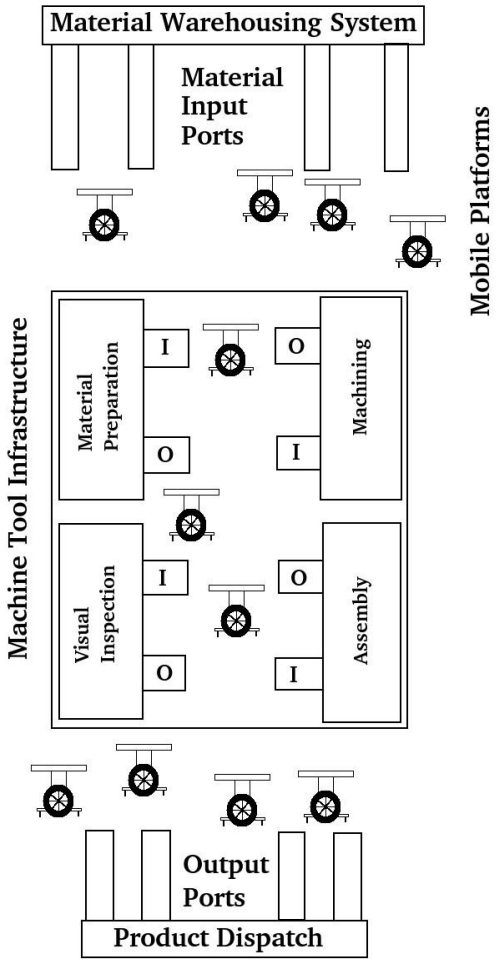

Figure 2. Layout of manufacturing system configured to mass produce custom products.

Design of a FMH platform architecture requires an understanding of the kinds of materials handling tasks which would be required of the materials handling agents. To better the design choices made during the development of the FMH platform architecture the materials handling tasks were split up into various contexts with respect to the mobile materials handling platforms and the volumes of transported loads. They are:

- Single platform low volume.
- Multiple cooperating platforms low volume with common load.
- Multiple cooperating platforms high volume with common load.
- Single platform high volume.

Current AGV systems carry out the first context in a repetitive manner. It is in the multiple platform contexts that platform architecture requires special attention. Multiple cooperating platforms transporting a common payload

should not transfer random forces between one another due to unanticipated and uncorrelated motion errors. The platforms developed during the research project used the articulation of the conveyor to absorb any disturbance forces brought on by motion errors of cooperating platforms. Task instances may require payload transfer between two or more platforms. The conveyor alignment system developed for the mobile platforms projects off exteroceptive sensor information to obtain global alignment. This procedure is also used to update platform orientation which is discussed in section 5.

3 Mobile Platform Design

3.1 Mobile Platform Architecture

By considering the various task instances, the platform was designed with the intention of creating a mobile base which could provide the means for effective operation in both the singular context and during cooperative tasks. The mobile platforms each contain these attributes:

- Differential drive system for planer motion control with two stabilising ball transfer units providing static balance.
- Servo operated driven conveyor belt with 2 *d.o.f* mounted on a rotary thrust bearing assembly (Figure. 4.) for material transfer between other platforms or machine tool bays.
- Proprioceptive and exteroceptive sensory infrastructures for use in pose estimation, obstacle avoidance and material transfer certainty.

Platform Design

The Drive Subsystem

The drive subsystem consists of an electronic drive control module, two 12V geared DC motors, two chain and sprocket power transmission units and quadrature encoders fitted to the wheel shafts for feedback. The wheel shafts are mounted between bearings to prevent any alignment errors from wearing out the quadrature encoder units. Figure. 3. shows the main components of the mechanical drive set up. One drive motor is removed for full view of support bearing. A differential drive base was chosen due to the simplified model representation of such systems. During multi-platform tasks the use of differential drive bases allows for a more precise estimation of platform orientation as slippage of the wheels is far less than the mechianical motion characteristics of omnidirectional wheel based mobile platforms.

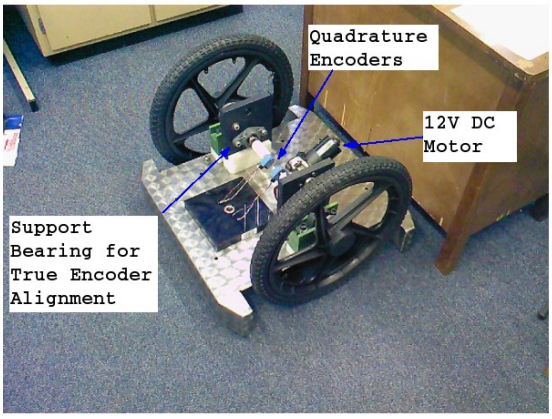

Figure. 3. Mechanical drive system.

The electronic drive control module consists of a PIC18C252 based embedded micro-controller namely the BrainStem® Moto 1.0 module [Acroname Inc.] which provides Pulse Width Modulation (PWM) and direction signals to two 20 Amp H-bridges. 256 count per revolution quadrature encoders provide a feedback control signal. The BrainStem® Moto 1.0 module was chosen as it is designed specifically for controlling differential drive robots. Utilising components directly intended for their required purpose produces cleaner system integration. The BrainStem® Moto 1.0 module has efficient PID control loops embedded in the module which can be configured between position and velocity control dynamically whilst the platforms are operational. Although one can obtain motor control modules with integrated motor drivers, separate H-bridges were used as they interface directly with the electrical characteristics of the geared DC motors. This allows system upgrades without breaking software infrastructures. This produces less downtime in industrial settings.

The Servo Conveyor Subsystem

The operational scope of the conveyor subsystem was split into two contexts. In a singular context the conveyor retrieves and dispatches small and medium sized materials between machine tools and other mobile platforms. For those purposes it acts as a multi-directional material conveyor. In the context of multi-platform cooperation during the transport of larger materials the conveyor subsystem is automatically configured to articulate thus providing arbitrary end connector trajectories, to be discussed under section 3.2. The conveyor belt and conveyor frame are driven and rotated by two 12V DC motors which are controlled by another PIC18C252 based embedded micro-controller namely the BrainStem® GP 1.0 module. The motors are driven via an IIC based motor driver which is housed on the IIC bus of the BrainStem® GP 1.0 module. The conveyor slides forward on linear bearings allowing for multi-platform material transportation, (section 3.2). The conveyor rests on a rotary housing and thrust bearing assembly. Both the thrust bearing assembly and the end connector assembly are fitted with quadrature encoders to provide conveyor and end connector orientations which monitor changes in payload

configuration using sensed articulations. [Abou-Samah *et al.* 2006].

Figure. 4. shows the mobile platform with a servo operated conveyor mounted on a thrust bearing on the left and the rotary housing and thrust bearing assembly on the right.

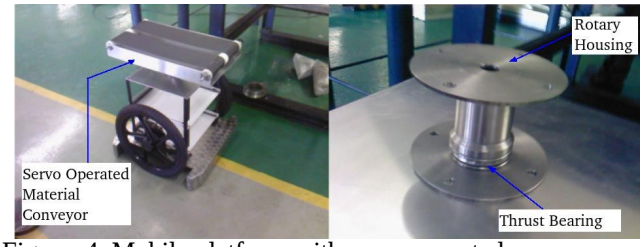

Figure. 4. Mobile platform with servo operated conveyor.

Computing and Data Acquisition Infrastructure.

The platforms on board computer is an AMD based single board computer running at 333MHz. The platform runs the Linux Operating System, the Fedora 7 distribution. The single board computer has six serial ports and four USB 2.0 ports. This added I/O infrastructure provides the grounds for future sensory system additions. A data acquisition board monitors the various battery voltages on the mobile platforms and is used to signal low power thus starting a recharging routine.

Sensory Infrastructures

A sonar array of 12 ultrasonic transducers provide the platform with exteroceptive sensor data, this data is used for local obstacle avoidance. The obstacle avoidance software mechanism will be discussed in section 4. The ultrasonic sensors are placed 30º apart and form a 360º ring. The firing sequence of the ultrasonic sensors is such as to try and minimise crosstalk between the sensors.

A screen shot of the mobile platforms sonar orientations and readings is shown below in Figure 5. At the time, the platform was connected to a desktop PC in the laboratory and was stationary.

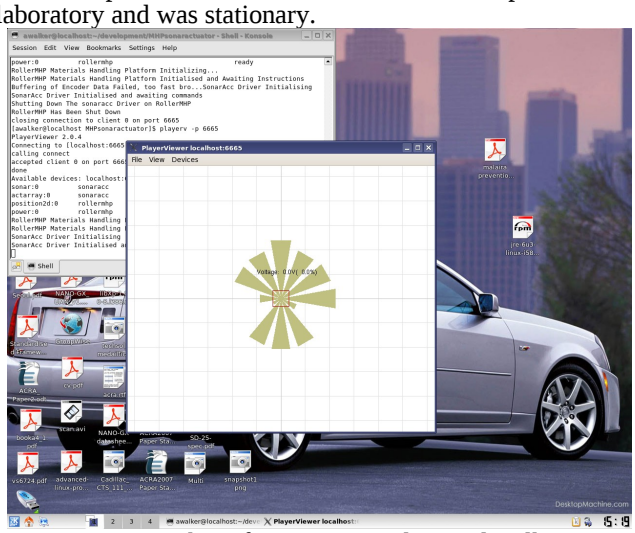
Figure 5. Screen shot of sonar sensor data on localhost.

Other sensors making up the platforms sensory infrastructure include an Inertial Measurement Unit (IMU) and a digital compass fitted to the underside of the conveyor. The significance of the digital compass is discussed under section 5.

Communication System

The platforms communicate with one another and other host computers over a wireless network. Each platform is equipped with an IEEE 802.11g wireless network adapter. Communication is performed through TCP/IP sockets.

3.2 The Kinematic Environment of the Mobile Platforms

A description of the kinematic environment of the mobile platforms is included here in order to provide insight into the choice of platform architecture.

Many control architectures have been developed to produce holonomic end connector trajectories in the constrained domain of nonholonomic mobile bases. The control architecture used here is derived from [Abou-Samah *et al.* 2006]. Figure. 6. depicts one mobile platform with the conveyor bearing mounted at the mid-point of the wheel axle.

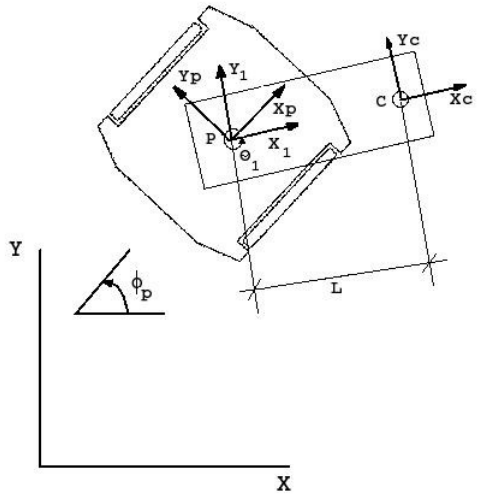

Figure. 6. Diagram of mobile platform and servo conveyor.

Reference frame {P} is rigidly attached to the mobile platform with the *X*-Axis in the direction of forward translation. Reference frame {1} is rigidly attached to the first revolute joint, i.e., the thrust bearing rotary housing. Reference frame {C} is rigidly attached to the connector, which is just a second smaller thrust bearing and bar assembly. The configuration of the connector on the servo conveyor can be parameterised by the relative angle θ_1.

The length from the main thrust bearing to the end connector is *L*. The configuration of the mobile platform is described by the position (X_p, Y_p) and the orientation Φ_P of frame {P} relative to some global frame {W}. The forward kinematics of the location of reference frame {C} with respect to the global reference frame {W} can be described as: (Abou-Samah *et al.* 2006).

$$\begin{bmatrix} Xc \\ Yc \end{bmatrix} = \begin{bmatrix} Xp \\ Yp \end{bmatrix} + Rot\left(\Phi_P\right) \times \begin{bmatrix} Lcos(\theta_1) \\ Lsin(\theta_1) \end{bmatrix}$$

$$where\ Rot\left(\Phi_P\right) = \begin{bmatrix} \cos(\Phi_P) & -\sin(\Phi_P) \\ \sin(\Phi_P) & \cos(\Phi_P) \end{bmatrix}$$

$$\Phi_c = \Phi_p + \theta_1 \quad (1)$$

3.3 Trajectory Creation Mechanism

The required end connector trajectory, as specified by the motion requirements of the payload, is mapped into the platform {P} reference frame as a required cartesian pose as well as linear and angular velocities for the mobile platform. [Abou-Samah *et al.* 2006]

Trajectory generation via mapping of arbitrary end connector trajectory

By locating the base of the conveyor at the midpoint of the axle creates a coupling between the angle of the thrust bearing rotary housing and the orientation of the mobile platform. This configuration of the articulation allows for a direct mapping of end connector trajectory into required platform motions without any nonholonomic influence. [Abou-Samah *et al*, 2006]

$$\gamma = \Phi_p + \theta_1 \quad (2)$$

Equation (1) can now be written as:

$$\Phi_C = \gamma$$

$$\begin{bmatrix} X_C \\ Y_C \end{bmatrix} = \begin{bmatrix} X_P \\ Y_P \end{bmatrix} + \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) \\ \sin(\gamma) & \cos(\gamma) \end{bmatrix} \times L \quad (3)$$

$$Where\ L = \begin{bmatrix} L \\ 0 \end{bmatrix}$$

Hence, given a desired end connector trajectory ($X_c^d(t)$, $Y_c^d(t)$, $\phi_c^d(t)$) , an expression for the required trajectory of the mobile platform can be determined as:

$$\gamma^r = \Phi_c^d$$

$$\begin{bmatrix} X_P^r \\ Y_P^r \end{bmatrix} = \begin{bmatrix} X_c^d \\ Y_C^d \end{bmatrix} - \begin{bmatrix} \cos(\gamma^d) & -\sin(\gamma^d) \\ \sin(\gamma^d) & \cos(\gamma^d) \end{bmatrix} \times L \quad (4)$$

At this stage the calculated $\gamma^r(t)$ can not be resolved into its required constituents, the orientation of the mobile platform $\phi_p{}^r(t)$ and the orientation of the conveyor $\theta_1{}^r(t)$.

Differentiating (4) under constant end connector displacement from the thrust bearing rotary housing we obtain the desired Cartesian velocity of the mobile platform as:

$$\dot{\gamma}^r = \dot{\Phi}_c^d$$

$$\begin{bmatrix} \dot{X}_P^r \\ \dot{Y}_P^r \end{bmatrix} = \begin{bmatrix} \dot{X}_C^d \\ \dot{Y}_C^d \end{bmatrix} - \begin{bmatrix} -\sin(\gamma^d) & -\cos(\gamma^d) \\ \cos(\gamma^d) & -\sin(\gamma^d) \end{bmatrix} \times L\dot{\gamma}^d \quad (5)$$

Since the reference frame {P} is rigidly attached to the mobile platform with the *X*-axis in the direction of forward translation. This configuration permits the unique determination of both the required orientation of the mobile platform $\Phi_p{}^r$ and the magnitude of the desired forward velocity $\upsilon_p{}^r$. [Abou-Samah *et al.* 2006].

$$\Phi_P^r = \arctan(\dot{Y}_P^r / \dot{X}_P^r) \quad (6)$$

$$\upsilon_P^r = \sqrt{\left[\left(\dot{X}_P^r\right)^2 + \left(\dot{Y}_P^r\right)^2\right]} \quad (7)$$

Differentiating (6) provides the required angular velocity for the mobile platform.

$$\omega_P^r = \left[\left(\dot{X}_P^r \ddot{Y}_P^r - \dot{Y}_P^r \ddot{X}_P^r\right) / \left(\dot{X}_P^r\right)^2\right] \cos^2(\Phi_P^r) \quad (8)$$

From this information, controllers can be developed to converge the actual mobile platform pose onto the required platform pose, interested readers are referred to [Abou-Samah *et al.* 2006] for greater insight.

4. The Software Architecture

4.1 Robot Servers and Generic Algorithm Development

In order to realise FMH systems the mobile platforms must communicate via well interpreted generic message passing primitives. Multi-platform cooperative materials handling algorithms should work with generic network interfaces to allow for generic algorithm development. To achieve this a well known robot server namely Player, [Collett *et al*. 2006.], was used as a Hardware Abstraction Layer (HAL). Many generic algorithms can be built into the Player server if required which can perform various tasks from obstacle avoidance to localisation. The platforms developed here use the Vector Field Histogram, [Borenstein *et* al. 1998], algorithm for local obstacle avoidance which was built into the server at compile time. Using the Player 2.0.4 API plug-in drivers were written to provide support for the control hardware used on the platforms. Four interfaces are supported on each platform via two plug-in drivers, Figure. 8., Figure. 7. shows a mobile platform with two device abstractions as well as their network addresses.

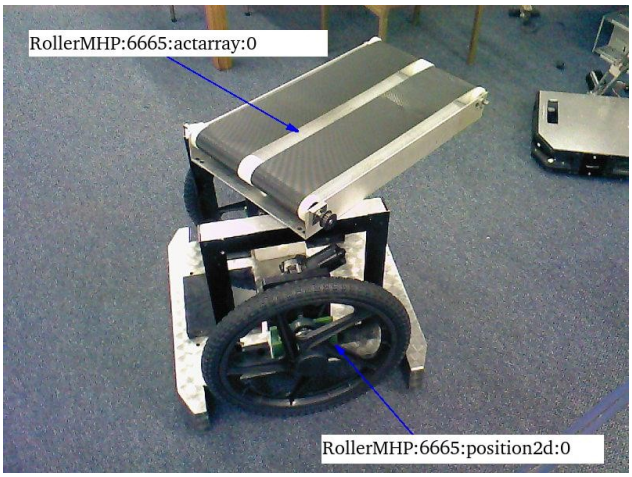

Figure. 7. Network abstractions for the mobile materials handling platform.

The servo operated conveyor was abstracted as an array of linear and rotary actuators via the actuator array interface, [Biggs, G. MacDonald, B. 2006]. This allows control of the conveyor system via message passing with generic actuators. The platforms drive system has been abstracted as a position2d device which can attain any configuration in SE(2). Other interfaces supported by the plug-in drivers are the power interface which monitors battery voltage to enable a recharging routine as part of the task scope of the platform. A sonar interface makes the sonar data available to all interested parties. For a full set of interface specifications the reader is referred to [playerstage.sourceforge.net].

Figure. 8. shows the layout of an instance of the Player server running on one of the platforms. The plug-in drivers are as modular as possible and each support only a minimal set of interfaces. This makes driver maintenance easier.

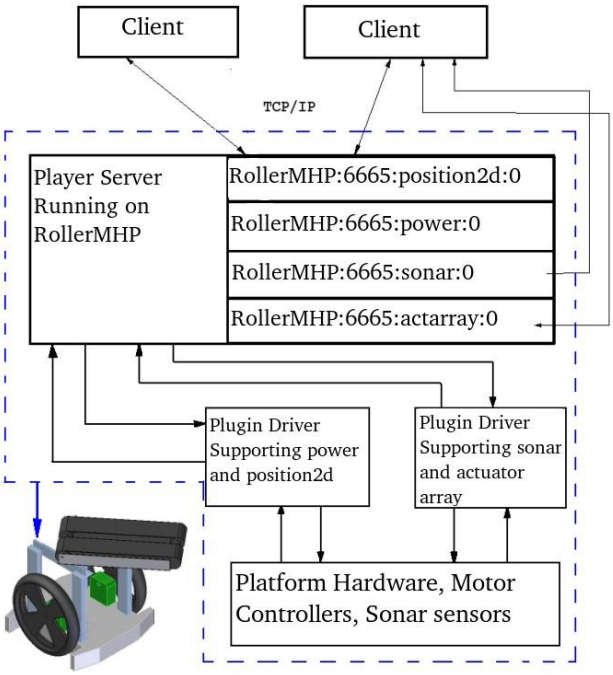

Figure. 8. Layout of an instance of the Player server running on one of the mobile materials handling platforms.

5. Discussion

The drive subsystem of the mobile platforms performed well during operation. On line tuning of the PID parameters provided smooth velocity control. The ability to configure the PID parameters during platform operation was beneficial and development is under way in producing a control loop tuning system which automatically configures the PID parameters based on the effective material loads seen by the mobile platforms. This will aid in allowing the platforms to retain optimal motion control as their physical bandwidths change with payload.

The conveyor alignment accuracy was tested for repeatability and performed well. This is a requirement if the platforms are to transfer materials between one another in a robust manner. The system works by utilising the signal from the digital compass to provide global conveyor orientation. When the platforms are in conveyor range the receiving platform then calculates the error between its conveyor orientation and the orientation of the conveyor transfering the payload. The error signal is used to drive the conveyor to the correct orientation. Once the payload has been successfully transferred both platforms update there orientation estimates by comparing their global and local orientation estimates. The local orientation is derived from the dead reckoning estimate of platform pose and the readings from the quadrature encoders fitted at the two articulations on the conveyor.

The Player Robot Server used in the research provided usable network interfaces without any modifications. The new Application Programming Interface (API) of the 2.0.x versions of the server allowed for the simple and efficient development of plug-in drivers achieving quick support of the hardware devices used by the mobile platforms. The Vector Field Histogram obstacle avoidance algorithm provided good local obstacle avoidance for the mobile platforms. Although the platforms designed in this paper are homogeneous in nature in the sense that they all have the same hardware and capabilities, this is not a requirement of such materials handling systems. Furthermore multi-agent cooperation and coordination algorithms parameterised by control bandwidths built using Players interfaces could allow for well behaved cooperation between heterogeneous materials handling platforms.

The platforms and device abstractions presented here try to maximise the operational scope of mobile materials handling infrastructures. These infrastructures provide a mechanism for the realisation of Flexible Materials Handling systems. These Flexible Materials Handling systems will still need higher level management systems, however, in order to achieve efficient mass production of customised products in future manufacturing systems.

6. Conclusion

A mobile platform architecture was developed which can operate effectively in singular context as well as during cooperative tasks involving multiple mobile platforms.

A Robot Server was utilised in providing the platforms with generic network interfaces and message passing primitives.

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