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Flexible Process Integration for Mass Customisation Manufacturing via Autonomous Mobile Payload Routing Platforms

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Abstract— **In this paper, the problem of providing flexible process integration for Mass Customisation Manufacturing is addressed. A subset of the total distributed process integration is assumed to be handled by flexible routing operations. Physical routing operations are considered to be facilitated by autonomous mobile Payload Routing Platforms (PRP's). Facility layout flexibility is extended through active material routing operations. A prototype mobile PRP is presented, which has been developed for preliminary testing and validation of the motion control associated with providing distributed process integration under customer-induced production dynamics.**

I. INTRODUCTION

The efficiency and effectiveness of production is highly dependant on the quality and tardiness of process integration systems. For decades, devices such as Automated Guided Vehicles (AGV's) have been used in providing distributed process integration. AGV's are applied between production infrastructure which, due to imposed constraints associated with facility layout configuration or required production flexibility, nullify the feasible utilisation of fixed-automation based infrastructure, such as conveyor and gantry systems.

Process integration can be considered as a two degree-of-freedom (d.o.f) design problem. Each d.o.f is partially correlated with the other and provides seperate solution methods. The passive d.o.f is the so called Facility Layout Problem (FLP), which is often treated in terms of the block layout configuration problem[1]. In such a problem space, departments, work stations, or cells, are sized and encapsulated in a bounding box that represents a block, and placed within the bounds of a production facility. The mathematical objective is to find a relative configuration of blocks that minimises total materials handling costs. One objective function is to minimise materials handling by adhering to an adjacency matrix[2]. Another is to explicitly minimise a material flow metric. The latter objective function uses a metric involving the flow volume between blocks, weighted by the unit cost of transporting such flow volumes, as well as a distance metric describing the absolute distance between blocks. By considering a production facility to be denoted by the region, $\mathcal{R}_P$, and the total extent of production infrastructure as a set of n block regions, $\Pi \triangleq \{\pi_1, \ldots, \pi_n\}$, the objective function can be described as,

$$\mathcal{OF} = \min \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} f(i,j)\, d(i,j,\mathcal{C}) \tag{1}$$

such that,

$$\pi_i \cap \pi_j = 0, \quad \pi_i \cap \bar{\mathcal{R}_{\mathcal{P}}} = 0,\ \forall \pi_i$$

Where, $f(i,j)$ denotes the unit-cost weighted flow volume between blocks i and j, and $d(i,j,\mathcal{C})$ represents the absolute distance, in terms of the respective metric used, between blocks i and j, in facility layout configuration $\mathcal{C}$. For AGV type materials handling systems, $d(.)$ represents the euclidean distance between block centroids.

Many FLP solutions have been developed over the past half century, from exact through to metaheuristic methods[3]. The majority of solutions are developed based on deterministic and time invariant material flow volume, which is derived from group technology analysis of a product mix[4]. A single distance metric is also used, although in more recent literature, heterogeneous distance metrics have been incorporated into the solution base[5]. Solutions developed under these assumptions are capable of producing optimally minimised objective functions under static product mixes, although could become unapplicable, even under marginal changes in product mix or production volume. Under such conditions, a reconfiguration in facility layout is required to suit changing flow volumes, which can be costly. The costs associated with such procedures can be so high, that it is not uncommon for production engineers to accept inefficient materials handling operations over investment in facility layout reconfiguration[6]. With modern consumerism establishing a need for high variety production operations, coupled with the current global economic recession, the development of effective process integration systems for manufacturing industries is becomming an increasingly important problem.

In order to increase flexibility in process integration, one can utilise the active design d.o.f, along with the large FLP solution base. This includes the development and application of materials handling systems with the flexibility to absorb variations in flow volumes, $f(i,j)$. The term flexibility is used here in the sense of structured flexibility, where initial efforts in developing solutions to a FLP produce layouts that are highly sensitive to changes in a product mix, or production volume. Therefore, flexibility is considered in

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terms of added materials handling and routing functionality that minimises the stimulation of plant reconfiguration procedures.

Mass Customisation Manufacturing (MCM) has been proposed to sustain modern consumer markets, and industrial economies[7]. MCM includes the design of manufacturing systems that are capable of producing fully customised products, at an efficiency that allows for costs to remain below those associated with upper market segments.

This paper addresses the development of materials handling and routing systems with the flexibility to provide distributed process integration for MCM. Process integration is considered to occur over uncorrelated material flow volumes and minimal stimulation of facility layout reconfiguration.

II. FLEXIBLE PROCESS INTEGRATION

With regard to the two d.o.f process integration design problem, this paper is explicitly concerned with the active d.o.f. It is assumed that the passive design d.o.f has been utilised in developing a facility layout around the expected or mean flow volumes associated with a particular MCM based Product Family Architecture[13], i.e. methods have been employed in order to minimise the objective function,

$$\mathcal{OF} = \min \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} E[f(i,j)]\, d(i,j,\mathcal{C}) \qquad (2)$$

such that,

$$\pi_i \cap \pi_j = 0, \quad \pi_i \cap \bar{\mathcal{R}}_P = 0, \forall \pi_i$$

Equation 2 represents the passive d.o.f in process integration system design, in which lower cost takes precedence over flexibility. As this paper addresses the active d.o.f, which increases process integration flexibility, a formal term will be used for its description. For this discussion, a Flexible Material Routing Primitive (FMRP) instance is considered as a composition of three basic phases;

- Material loading phase
- Material transportation phase
- Material unloading phase

Both the material loading and unloading phases are crutial in providing robust material payload transfer. In this sense they can be treated as an equivalent materials handling task. The transportation phase does not explicitly concern the handling of materials, but rather, the gross movement of material between distributed production infrastructure. Each phase type, i.e. either handling or transportation, has a seperate motion control requirement, Fig. 1.

In Figure 1, the Region of Convergence (RoC) is a restricted space, and allows for higher-level mutually exclusive access rights to input/output ports. At any particular instant, only one PRP may be operating inside the RoC. Incorporating these regions into the operating environment of mobile PRP's would allow for the application of robust materials handling management structures, such as those proposed in[8]. The border of a RoC represents a transition zone for the type of motion control required during FMRP task execution. Inside the RoC, motion control is in the form of posture stabilisation. This is a critical motion requirement, in which the mobile payload routing platform aligns itself, i.e. achieves a required planar position and orientation $[x_p,\, y_p,\, \theta_p]^T$, with an input/output port.

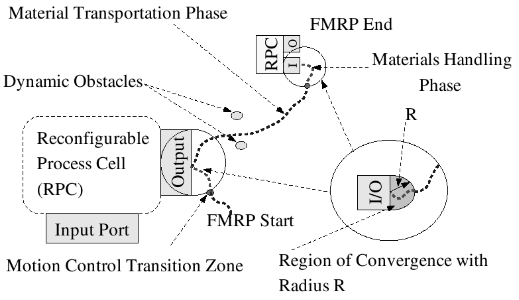

Fig. 1. The different motion control zones of a Flexible Material Routing Primitive (FMRP)

Outside the RoC, motion occurs as a result of the outputs from local and global navigation operations, performed by autonomous systems implemented on the mobile PRP's.

Two seperate motion control environments may seem arbitrary. However, these notions of RoC and the associated motion control primitives are analogous to the control architectures implemented in satellite attitude control systems. In such systems, the control infrastructure is distributed and performs a different control function based on its accuracy, repeatability, and power consumption. For example, in the attitude adjustment of a satellite's communications equipment with a receiver on earth, relatively powerful thrusters are used for large attitude adjustments, and smaller more accurate magnetic torque generators for final alignment of the communications infrastructure. In much the same manner, the transportation phase provides material payloads with large initial displacements. These large displacements are only specified in terms of maintaining real-time obstacle avoidance, independant of absolute accuracy of repeatability, as long as such motions terminate somewhere on the border of a RoC. On the other hand, the materials handling phase is used to achieve final required alignment of the mobile PRP and associated materials handling hardware with an input/output port, to ensure successful and robust material payload transfer.

III. A GENERIC IMPLEMENTATION ARCHITECTURE

Engineering architectures create structured encapsulation of concepts and specifications required to implement scalable systems. Following in this approach, an Implementation Architecture (IA) is proposed here to encapsulate core capabilities for FMRP execution. The architecture is termed the Autonomous Material Transportation Specification (AMTS).

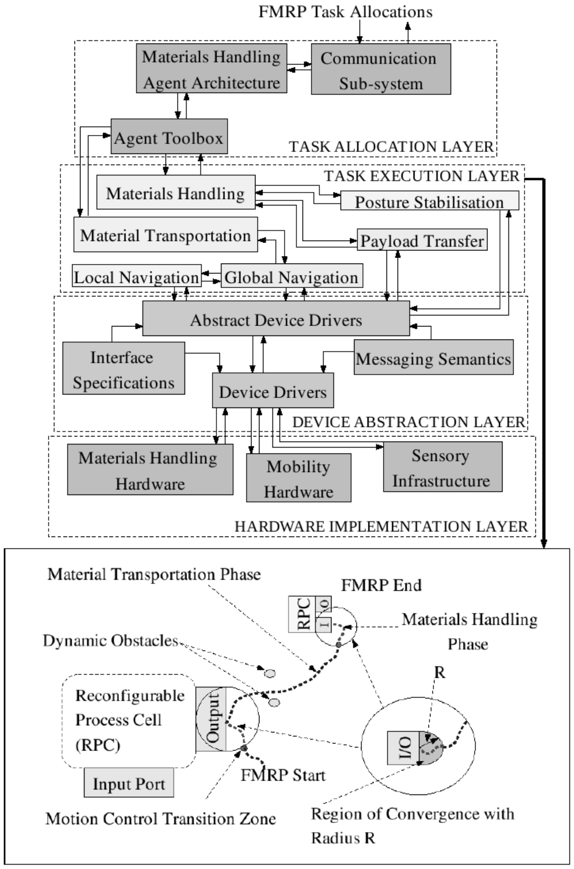

Fig. 2. Autonomous Material Transportation Specification

It is layered, hierarchial, and consists of four main functional levels, Fig. 2.

A. Top-Down Overview

To conserve generality in the AMTS, the architecture extends from system scoped concepts down through hardware implementation. The *Task Allocation Layer* serves to manage the logical and strucural execution of active process integration. Instances in which a "critical section" of consecutive process integration operations are required, this layer facilitates mutual exclusion operability. These critical sections can arise when assembly operations require consecutive delivery of components in order to initiate. Higher level management systems can use this layer to lock a "mutex" on a mobile PRP, execute the critical section of FMRP instances, and then release the mutex upon completion. Purposefully, this layer implements structured management over an unstructured production plant. Real-time specifications on FMRP task execution are managed in this layer. These functions are handled collectively by a *Materials Handling Agent Architecture*.

Required motion for FMRP task execution is handled from first principles. In this light, a material payload requires a change in location between distributed process cells as well as a transformation from an initial pose to a goal pose. The latter requires a materials handling operation and the former, a material transportation operation. In order to maintain robust and repeatible FMRP task execution, the *Task Execution Layer* provides the two stage control architecture discussed in section II. All materials handling operations are handled in the *Materials Handling* motion control block. Motion controllers are in the form of full state feeback stabilizers and inverse kinematic frameworks. Full state feedback stabilizers need to be Lyapunov stable with asymptotic convergence capabilities of polynomial or exponential characteristic. This is to ensure that the PRP's trajectory remains within the RoC during operation. Material transportation operations are facilitated by local and global navigation functions. Due to the unstructured environments of MCM production plant, the output motions from navigation functions are specified in terms of achieving real-time obstacle avoidance and path planning.

The heterogeneous nature of hardware implementations used in active process integration systems presents a discontinuity between system and process levels in manufacturing. To increase scalability in the AMTS, the *Device Abstraction Layer* provides a "Hardware Abstraction Layer" between physical PRP implementations and the control and management systems which operate on them. This layer abstracts hardware specifics into generic abstractions associated with the motion control requirements of the *Task Execution Layer*. Motion control algorithms are therefore developed to operate on generic abstractions which increases scalability in control software. This layer serves as a complexity mask for the *Task Execution Layer*.

Hardware implementations in active process integration are application specific. Therefore the AMTS places specifications on hardware capabilities, in providing the necessary infrastructure to facilitate material payload routing from first principles. The minimum motion required by a PRP to transport a material payload between distributed process cells is planar translation and rotation. The *Mobility Hardware* block is therefore specified in terms of achieving any configuration on $\mathbb{R}^2$ X SO^1. This is a reasonable specification as the majority of factory floors are smooth and flat due to safety requirements. The *Materials Handling Hardware* block is specified in terms of its ability to manipulate a material payload relative to the underlying transportation hardware. A payload provided n d.o.f through transportation must have $n + 1$ d.o.f through the combination of transportation and handling. Development of sensory perception systems for autonomous navigation in MCM manufacturing environments is a complex task. In order to better local and gloabal navigation operability, the *Sensory Infrastructure* block is specified in terms of providing active sensory perception around the entire periphery of a PRP. This allows for directionally unbiased obstacle avoidance capabilities for PRP's in unstructured MCM plants.

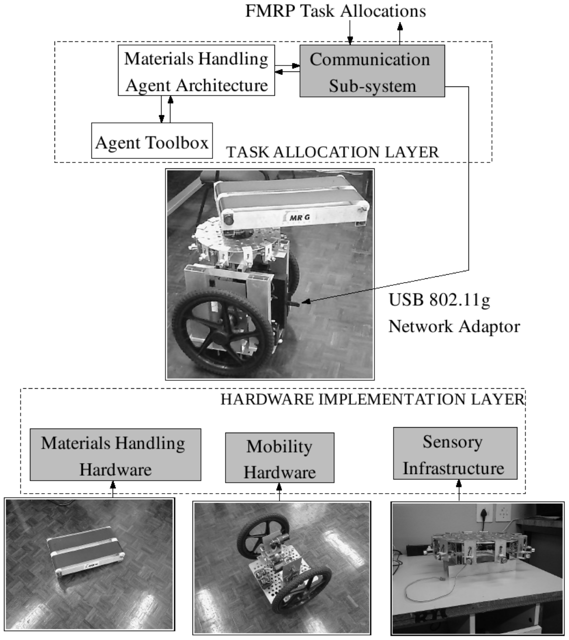

Fig. 3. An instance of the HIL of the AMTS in the form of a Linux based PRP

IV. A PHYSICAL INSTANCE OF THE ATMS

A prototype mobile PRP has been developed in alignment with a subset of the specifications in the AMTS. The platform provides a testbed for research in flexible process integration for MCM via FMRP's.

Physical realisation of the *Mobility Hardware* block is in the form of a differential drive base with embedded PID control infrastructure and odometic capabilities. This is provided by a PIC18 based embedded microcontroller and associated drive and feedback infrastructure. Exteroceptive sensors provide 360° perception. Each ultrasonic transducer operates at 40KHz. The sonar array is a stand alone system and is handled locally through an onboard embedded microcontroller that makes range readings accessible through a serial UART. The *Materials Handling Hardware* block is a rotary conveyor, which can both translate as well as rotate a payload with respect to the underlying transportation infrastructure. The rotary conveyor system is operated through an embedded microcontroller. The PRP itself is considered as a collection of devices, constituting the integration of the three sub-blocks of the *Hardware Implementation Layer*, rather than a monolithic mobile robot platform. The PRP's onboard computing infrastructure is in the form of a Mini-ITX form factor single board computer running at 1.5GHz. The onboard computer acts to integrate the three embedded sub-systems and runs Linux, Fig.3.

To provide the mobile PRP with Hardware Abstraction Layer functionality, the Player Robot Device Interface [9] was used, which allows for the development of network scoped and scalable control architectures. Player is a C/C++ implementation of a robot orientated Hardware Abstraction Layer. Player's most commonly used runtime implementation is in the form of a client-server model in which client applications control hardware through passing messages between client computers and a server located on the robot, through local proxy's over a TCP/IP network, Fig. 4. For a comprehensive overview of Player's design and implementation, see http://playerstage.sourceforge.net.

Task execution is split according to occupancy of a RoC. Currently, for transportation instances outside a RoC, the mobile PRP is capable of performing local navigation operations. Global navigational capabilities are currently being developed for the PRP. Local navigation is provided by the Vector Field Histogram+ (VFH+) real-time obstacle avoidance algorithm[10]. A generic implementation of the VFH+ forms part of the code base of the Player robot device interface, allowing quick and easy application of the algorithm to multiple robot platforms after such platforms have been supported under Player's HAL functionality.

For motion requirements associated with materials handling operations, i.e. inside a RoC, a Lyapunov stable motion controller has been implemented and provides the mobile PRP with asymptotic feedback stabilisation from an arbitrary initial configuration $[x_i, y_i, \theta_i]^T$ to a final goal configuration around an input/output port $[x_p, y_p, \theta_p]^T$. The drawback associated with implementing the *Mobility Hardware* device as a differential drive platform are the associated differential constriants regarding the application of full state feedback stabilisation controllers. Differential drives are nonholonomic systems and do not satisfy Brockett's theorem for smooth feedback stabilisability, which states that in order for a system to be stabilised onto the origin of its configuration space via smooth, time-invariant feedback control, the fully qualified closed loop vector fields must be continuous around the origin[11]. To overcome the constriants imposed by the differential drive and exposed by Brockett's theorem, a nonlinear control law was implemented that transforms the differential drives Cartesian configuration space into a Polar coordinate based configuration space, Fig. 5 and (3) through (5)[12].

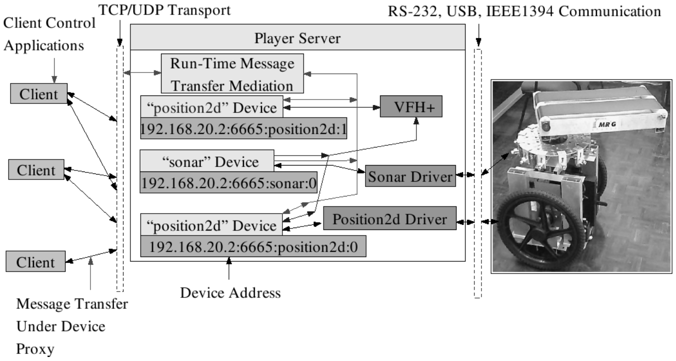

Fig. 4. HAL functionality provided by the Player Robot Device Interface, and implemented on the mobile PRP

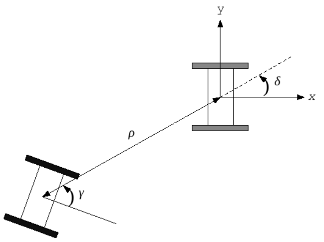

Fig. 5. Polar coordinate transformation which overcomes Brockett's condition for smooth feedback stabilisability

$$\rho = \sqrt{x^2 + y^2} \tag{3}$$

$$\gamma = \tan^{-1}\left(\frac{y}{x}\right) - \theta + \pi \tag{4}$$

$$\delta = \gamma + \theta \tag{5}$$

Using this new coordinate system, the system model, in the form of state differential equations, for a differential drive becomes characterised by a singularity at the origin of the PRP's configuration space, (6) through (8)[12].

$$\dot{\rho} = -\cos\gamma\, v \tag{6}$$

$$\dot{\gamma} = \frac{\sin\gamma}{\rho}\, v - \omega \tag{7}$$

$$\dot{\delta} = \frac{\sin\gamma}{\rho}\, v \tag{8}$$

The following non-linear control law was used in setting up the necessary feedback vector fields to produce a globally asymptotic and stable equilibrium point at the origin of the PRP's configuration space, (9) and (10)[12].

$$v = k_1\, \rho \cos\gamma \tag{9}$$

$$\omega = k_2\, \gamma + k_1\, \frac{\sin\gamma\cos\gamma}{\gamma}\,(\gamma + k_3\, \delta) \tag{10}$$

Where, k_1, k_2, and k_3 are the tuning parameters.

The nonlinear motion controller was implemented and tested on the prototype PRP. Multiple online tests allowed for the tuning of the control law to enable effective operation of the PRP during required posture stabilisation operations. The response characteristics of the motion controller is shown from two different initial poses, Figs. 6 and 7. As can be seen by the responces, even in the worst case situation, in which the mobile PRP is asked to perform a lateral displacement, which is a direct violation of its differential constraints, the mobile PRP effectively performs the required task. The control law provides a vary natural response with good repeatability characteristics. Figure 8 shows the PRP's position trajectory during a parallel parking maneuver.

V. DISCUSSION

Fundamentally, modern production problems are solved in a system scope where each subsystem is well integrated with the rest of the manufacturing system. This vertical integration is of utmost importance in facilitating MCM production operations, where customer induced production variations must be absorbed by flexible production infrastructure and

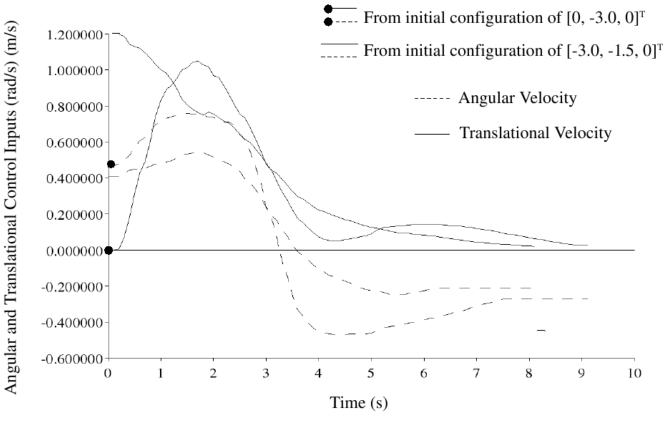

Fig. 6. Control input convergance from two seperate initial conditions

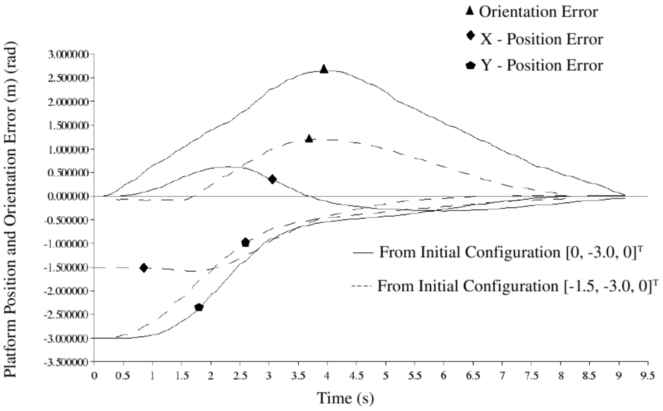

Fig. 7. State convergence from two seperate initial conditions

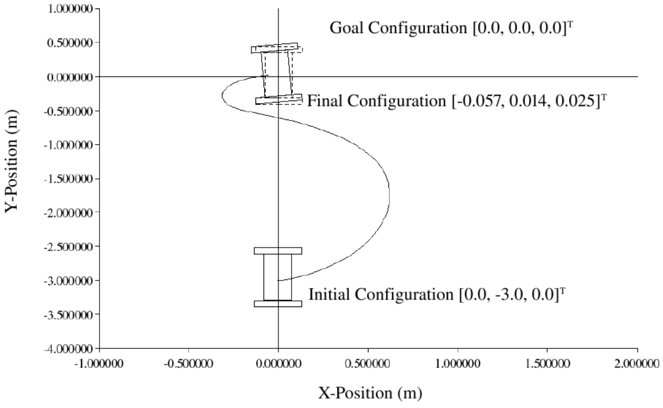

Fig. 8. Position trajectory for a parallel parking maneuver

process integration systems. The extension of current AGV technologies to include autonomous mobile Payload Routing Platforms, capable of performing arbitrary routing operations, can only aid in developing effective process integration in MCM production environments. Developing a motion control framework based on two motion control environments seperated by a restricted region around an input/output port, would allow for highly repeatable and accurate material payload routing operations by switching to more accurate control structures as the mobile PRP's approach a target input/output port. The current mobile PRP implementation has adequate motion performance around conceptual RoC, with the polar coordinate based feedback stabilisation control law providing asymptotic convergence properties. The IA developed here allows for common model development of the active d.o.f for flexible process integration systems. The mobile PRP presented here is currently under further development in the transportation aspects of FMRP's, such as global navigation operations.

VI. CONCLUSION

In this paper, the problem associated with providing flexible process integration for Mass Customisation Manufacturing production environments was addressed in terms of a two d.o.f design problem. The passive d.o.f was considered to be the Facility Layout Problem, which has had much attention over the past half century. Due to customer induced variations in flow volumes, associated with the facilitation of MCM production operations and modern consumerism, an active d.o.f was proposed as an additional design degree of freedom in achieving effective and flexible process integration. A mobile Payload Routing Platform (PRP) was presented, developed in alignment with an Implementation Architecture that encapsulates the core functional requirements associated with implementing flexible process integration operations in MCM production environments. The PRP acted as a testbed for the motion control requirements for flexible process integration task execution. A nonlinear motion contoller was implemented to provide the mobile PRP with posture stabilisation, which performed well and provided the PRP with natural motion responses.

VII. ACKNOWLEDGMENTS

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REFERENCES

[1] Wu, Y. and Appleton, E., "The optimisation of block layout and aisle structure by a genetic algorithm" *Computers & Industrial Engineering*, vol. 41, 2002, pp 371-387.

[2] Tate, D. M. and A. E. Smith, "Unequal-area facility layout by genetic search", *IEEE Transactions*, vol. 27, 1995, pp 465-472.

[3] Meller, R.D. and K.Y. Gau, "The facility layout problem: recent and emerging trends and perspectives,"*Journal of Manufacturing Systems*, vol. 15, 1996, pp 351-366.

[4] Mikell. P. Groover, "Automation, Production Systems and Computer Integrated Manufacturing Systems", *Prentice Hall, Inc*, 1987, ISBN 0-13-054610-0.

[5] G. Ozedemir, A.E. Smith, B.A. Norman, "Incorporating Heterogeneous Distance Metrics Within Block Layout Design,"*International Journal of Production Research*, September 2002 (Accepted paper).

[6] S. Benjafaar, S.S. Heragu, S.A. IraniMeller, R.D. and K.Y. Gau, "Next Generation Factory Layouts: Research Challanges and Recent Progress,"*INFORMS*, vol. 32, No. 6, 2002, pp 58-76.

[7] J. Pine, "Mass Customisation - the New Frontier in Business Competition,"*McGraw-Hill*, 1993.

[8] Walker, A.J and Bright, G., "Standardised Framework for Flexible Materials Handling Management based on Operating Systems Primitives,"*In Proc. of the 2007 Australasian Conference on Robotics and Automation*, Brisbane Australia, December 2007 (on cd).

[9] T. Collett, B.A. MacDonald, B.P. Gerkey, "Player 2.0: Toward a practial robot programming framework,"*In Proc. of the 2005 Australasian Conference on Robotics and Automation*, Sydney Australia, December 2005 (on cd).

[10] I. Ulrich and J. Borenstein., "VFH+: Reliable Obstacle Avoidance for Fast Mobile Robots,"*In Proceedings of the 1998 International Conference on Robotics and Automation*, Leuven Belgium, May 1998, pp 1572-1577.

[11] Brockett, R.W., "Asymptotic Stability and Feedback Stabilization". *In: Differential Geometric Control Theory*(R.W. Brockett, R.S. Millman and H. J. Sussmann, Eds), pp 181-191.

[12] Vendittelli. M, De Luca. A, Oriolo. G., "Control of Wheeled Mobile Robots: An Experimental Overview,"*In RAMSETE: Articulated and Mobile Robots for SErvices and TEchnology*, vol. 270, 2000.

[13] Jioa. J, and Tseng. M.M, "A methadology of developing product family architecture for mass customization", *Journal of Intelligent Manufacturing*, vol. 10, 1999, pp. 3-20