A Low Cost, Modular, and Reconfigurable Manufacturing Cell for Construction of Heterogeneous Micro-Nano Systems

Aditya N. Das and Stephen Savoie

University of Texas at Arlington Research Institute (UTARI)
7300 Jack Newell Blvd. S., Fort Worth, TX 76118, USA
Phone: 817 272 5970, Fax: 817 272 5946, E-mail: aditya@uta.edu

ABSTRACT

This paper presents a novel, low-cost, and easily customizable manufacturing system for heterogeneous micro-nano systems construction. In contrast to the commercially available expensive, rigid, and skill-intensive-automation-based high precision robotic manipulation systems suitable for sub-millimeter scale assembly and packaging, the proposed manufacturing system incorporates one-of-its-kind multifunctional interconnect technology along with a novel uncertainty-propagation estimation method to configure and optimize for the necessary and sufficient manufacturing platform to construct heterogeneous micro-nano systems via automated 3D assembly. The unique design of the hardware and software allows commercially viable low-volume manufacturing and new productization. Furthermore, a proprietary software application holistically analyzes the entire manufacturing process for a typical micro-nano system and quantitatively predicts the manufacturability metrics such as production yield, cycle time, overall cost, and device performance. This concurrent evolution of the product and the factory significantly reduces the number of iterations in product development, thereby making manufacturing in such specialized cases faster, better, and cheaper.

Keywords: heterogeneous microsystems, flexible manufacturing, rapid prototyping, manufacturing optimization, portable precision manipulators

1 INTRODUCTION

Heterogeneous micro-nanosystems hold a vital position in next generation products as miniaturization technology grows more and more popular. As opposed to their conventional predecessors, monolithically fabricated using legacy semiconductor industry methods that are highly expensive and result in limited functionalities, the new heterogeneous micro-nanosystems, constructed via assembly, promise superior quality, reliability and dramatically extended range of new products. In order to promote exploration in this domain and enable rapid prototyping to validate new product ideas, suitable manufacturing tools must be made available. Furthermore, such tools must be inexpensive, flexible, and reliable in order to not only encourage new researches and startups but also facilitate seamless technology transition. In this paper, we present such a technology, namely a modular and reconfigurable manufacturing cell, for easy prototyping and pilot production in millimeter and sub-millimeter scale.

The *"modular and reconfigurable manufacturing cell"* or MRMC (see Figure 1) is a flexible system integration platform, having modular robotic hardware and tools, which can selectively configure itself for different tasks. Key features are:

- Designed for fast, inexpensive reconfiguration
- Offers on-demand, on-site prototyping/pilot production
- Scalable and portable
- Built-in artificial intelligence for self identification and easy automation setup
- Suitable for low to medium volume production

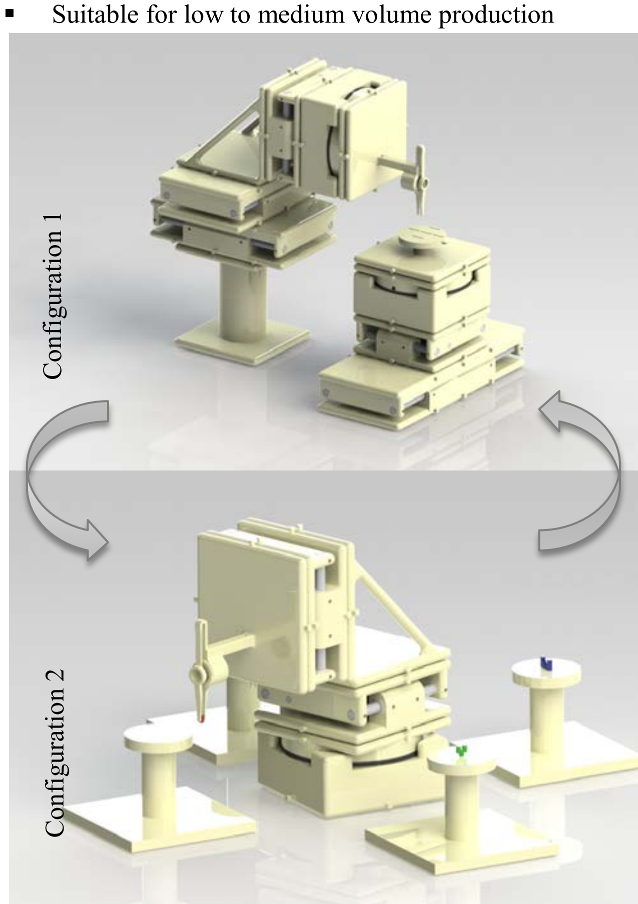


Figure 1: 3D rendering of the MRMC.

The custom developed MRMC modules use a novel multifunctional interconnection technique that significantly reduces configuration time and simplifies the transition between configurations for different product integrations. A custom designed and distributed intelligence based automation software is used to automatically identify the MRMC configuration and implement a novel precision optimized motion planning and control technique ensuring high yield manufacturing. When production volume for a product is reached, the MRMC can be quickly and easily dismantled and rebuilt into a different configuration. These configurations are quantitatively optimized by a proprietary manufacturing design software called *"Design for Multiscale Manufacturing"* or DfM^2. Figure 2 shows a snapshot of the DfM^2 software interface.

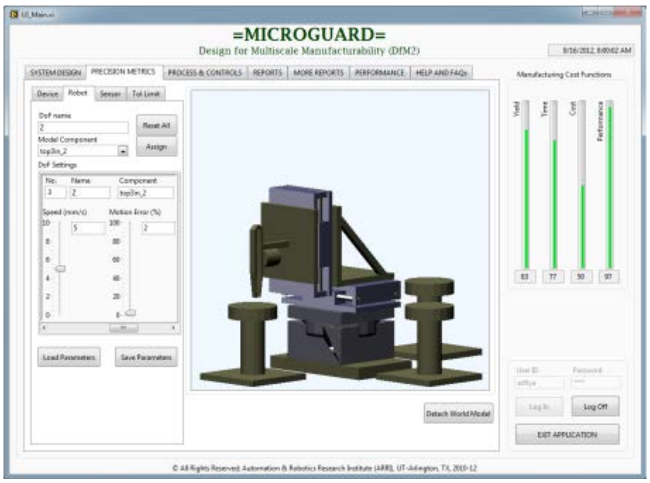


Figure 2: Snapshot of the DfM^2 software.

The subsequent sections of this paper will present the development of the MRMC prototype, its specifications, control and operations, and characterization results.

2 MRMC PROTOTYPE DEVELOPMENT

The modular and reconfigurable manufacturing cell (MRMC) prototype consists of several linear and rotational manipulation modules, different connecting fixtures, and multiple end-effectors.

2.1 Manipulation Modules

The prototype system consists of linear manipulation modules of three different ranges of motion i.e. 30mm, 50mm and 70mm. The rotation module is capable of full 360^o rotation. Among the different modular fixtures there are quick-build base plates, sample holders, and 90^o angle brackets. Two different types of modular end-effectors, an electromagnetic gripper and a dispenser, have been designed and developed to achieve typical pick & place and bonding operations. Figure 3 shows the actual hardware test-bed at our laboratory.

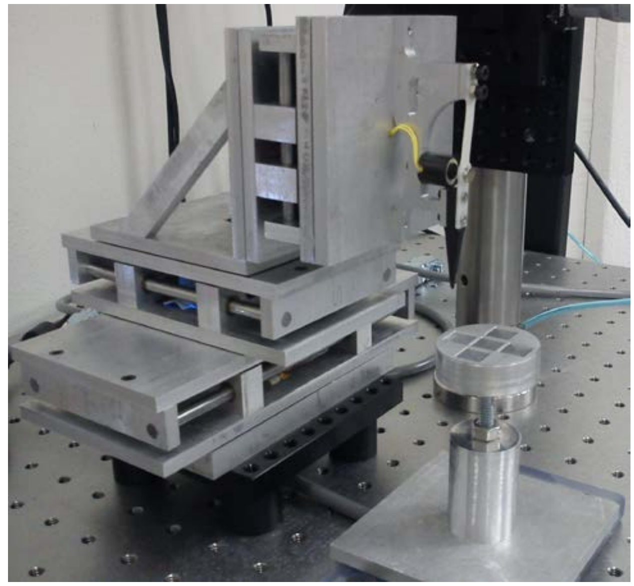


Figure 3: MRMC prototype developed in laboratory.

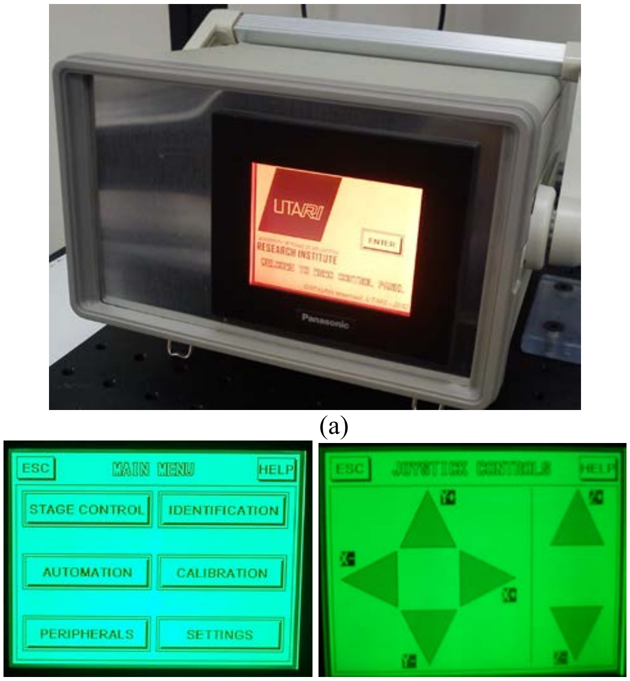
These manipulation units use a 2.4Watt stepper motor with a lead screw that moves the stage. Standard 1/4th inch graphite code bearings house the two stainless steel shafts that guide the motion of the stage. The aluminum body of the manipulation stage has been CNC machined.

Apart from these components, each manipulation module also consists of a *novel and proprietary multifunctional interconnect* that allows mechanical as well as electrical connectivity between modules, fixtures, and end-effectors. This interconnect component consists of an orientation independent magnetic locking mechanism, which allows mounting of the manipulation modules in any of the four orthogonal orientations i.e. at 0^o, 90^o, 180^o or 270^o. Furthermore, the multifunctional interconnect component also includes microcontroller circuitry to provide local processing capability. The end-effectors and other fixtures also incorporate the multifunctional interconnect in their design for seamless and rapid integration with the manipulation system.

Several end-effectors also are a part of the MRMC. Among them there is an electromagnetic gripper, which uses an electromagnet and a permanent magnet. A balanced force based actuation principle allows smooth, bi-directional operation of the gripper. Among other types of end-effectors, the MRMC also has a quick-change dispensing head.

2.2 Motion Controller

A custom designed motion control PCB interfaces the manipulation modules with motor drives, peripherals such as a touch screen panel and a vacuum generator, and the computer. As opposed to the 1:1 mapping between motor drives and manipulation units in case of commercial systems, this controller enables 1:8 mapping of motor drive and manipulator. Through a multiplexed signaling architecture, the MRMC controller enables a single motor driver to run up to 8 manipulators. Figure 4 shows a picture of the controller along with a few snapshots of the touch screen interface.



(a)

(b) (c)

Figure 4: (a) MRMC controller box and (b, c) touch panel snapshots.

2.3 Communication Protocols

The MRMC uses four types of communication protocols to interface various modules of the system. The touch panel has been interfaced with the main controller via a full-duplex serial communication. Different manipulation modules are connected to each other and to the main controller over an I^2C bus. USB connectivity has been established in between the main controller and computer. Lastly a few time-critical communication channels have been hard-wired.

2.4 Other Peripheral Units

Different peripheral units such as a microscope, a vacuum pump, a data acquisition module, etc. have also been integrated with the MRMC. These peripheral modules are used in different types of operations executing the custom automation plans.

2.5 Human-Robot Interface

In order to make the flexible manufacturing cell easy to deploy and easy to use, a portable console has been designed. This console uses two joysticks and one display board. It allows the operator to manipulate the robots as well as control the end-effectors and other peripherals. The MRMC can be operated in three modes: manual, semi-automated, and fully automated. A single USB connection to the controller box, as shown in Figure 4, allows seamless execution of the assembly tasks.

3 MRMC PROTOTYPE SPECIFICATIONS

The MRMC prototype module specifications are shown in Table 1.

Parameter	Value	Unit
Resolution	4 to 15	µm
Range of motion (linear module)	30 to 70	mm
Range of motion (rotation module)	360	degrees
Maximum thrust	10	lb
Maximum speed	3	mm/sec
Pull force limit of interconnects	20	lb
Motor type	Stepper	-
Motor power rating	5/0.25	Volt/Ampere
System power rating	24/0.9	Volt/Ampere
Typical configuration time	< 2	minutes
Typical calibration/ program time	< 5	minutes
Manipulation module cost	~ 300	$
Controller system cost	~ 500	$
Manipulators per controller	8	-
Size (length x width x height)	(90-185) x 90 x 35	mm^3
Weight	420 to 780	grams
Individual cabling to manipulator	Not required	-
Communication frequency	10	KHz
Computation frequency	20	MHz
Stand-alone interface	Touch panel	-
PC connectivity	USB	-
Configuration identification	Automatic	-
Assembly automation mode	Programmable	-

Table 1: MRMC prototype module specifications.

Some of the unique features in the presented modular and reconfigurable manufacturing cell are:

1. Fully automated robotic prototyping system
2. Intelligent robotic modules with distributed intelligence
    a. Modules can automatically identify their position and orientation in the system

b. Multiple modules can be operated by a single controller via bi-directional communication
c. Entire system can be programmed & controlled by a master controller without the need for a computer
3. Extremely portable architecture
a. No nuts and bolts needed
b. No complicated wiring needed
c. Low form factor controller unit
4. Commercialization friendly, as compared to conventional manipulation modules in market
a. Lower cost
b. Competitive precision output
c. Improved force output
5. Revolutionary design enabled extreme flexibility for rapid product transition

4 PRECISION AND FLEXIBILITY

One of the major challenges in flexible manufacturing architecture, where system components are frequently reorganized to accommodate changes in tasks, is to guarantee necessary and sufficient precision metrics such as resolution, repeatability, and accuracy. In our past work [1], we have investigated the effect of parametric uncertainties in a serial robot chain composed of prismatic or rotary modules on the overall positioning uncertainty at the end-effector. We used our proprietary iterative analysis software called *"Design for Multiscale Manufacturability"* (DfM^2), as mentioned in [2], in order to implement the uncertainty propagation estimation algorithms and build a statistical model of the common manufacturing metrics, such as production yield, cycle time, and overall cost.

We tested two configurations, as shown in Figure 1, using the same MRMC modules. Using the DfM^2 software we simulated a thousand cycles of a pick and place task by the two configurations. Table 2 shows the results.

Robot configuration	Yield	Cost	Time
1 (Figure 1 top)	83%	50%	77%
2 (Figure 1 bottom)	92%	48%	80%

Table 2: Usability assessment of the MRMC.

For the purpose of benchmarking we used the yield, cost, and time information for a commercially available conventional robotic manipulation system, which are 99%, $3,600, and 4 minutes respectively. The results for the yield, cost and time in the case of the MRMC robots, as shown in table 2, are the percentages of these benchmark numbers.

From the results, it has been concluded that the MRMC offers a low-cost, competitive alternative to its conventional counterparts. Although the yield is lower in the case of the MRMC, we envision that it can be improved further with more robust mechanical design for the modules and the automation control techniques.

5 CONCLUSION

In this paper we presented a novel flexible manufacturing system offering rapid prototyping capability at low cost, which is ideal for low to medium volume manufacturing. The unique hardware presented in this work is of much lower cost in comparison to similar commercially available manipulation modules.

The key to the success in this case is the concurrent engineering of the product and the factory, both simultaneously. The holism in this framework is aided by fast and reliable modeling of the entire process via a collection of interdisciplinary analytical, simulation-based, and experimental techniques. Concept realization and implementation are enabled through an entirely new class of robotic hardware and intelligent software applications.

The proposed effort is envisioned to make manufacturing independent of products, tools, sites, and production volumes. Figure 5 shows a 3D rendering of the vision for next generation manufacturing platforms where manufacturing robots are automatically configured using MRMC modules and then these robots build the product.

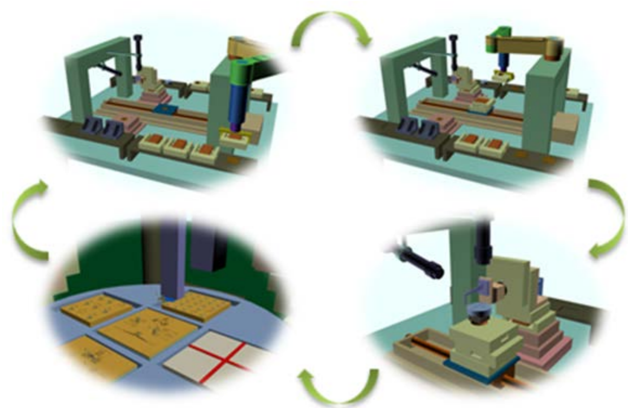


Figure 5: Concept rendering of automatically reconfiguring factory for on-demand, on-site manufacturing.

The authors would like to extend their gratitude towards the office of naval research (ONR) for supporting this work.

REFERENCES

[1] A. N. Das, D. Popa, H. E. Stephanou, *"Precision Evaluation of Modular Multiscale Robots for Peg-in-Hole Microassembly Tasks,"* in Proceedings of International Conference on Intelligent Robots and Systems (IROS), San Francisco, California, USA, pp. 1699 – 1704, Sep. 2011.
[2] A. N. Das, H. E. Stephanou, *"Concurrent Engineering in A Microfactory,"* in Proceedings of Commercialization of Micro-Nano Systems Conference (COMS), Greensboro, North Carolina, USA, August, 2011.