OVERVIEW
This abstract presents the design and operation of a micro-scale robotic system which is used to manipulate and measure micrometer size components for the purpose of positioning and assembly. Components are gripped using a 3 fingered ‘hand’ with pick-and-place being provided by a three axis moving ‘factory floor’. Finger displacement sensors and fingertip force sensing provides grip and dimensional feedback while cameras and a multi-function ‘joystick’ enable an operator to remotely control the assembly process. Examples of stacked spheres on a razor blade edge and an assembled proximity probe are presented to demonstrate the system capability.

INTRODUCTION
Additive and reductive manufacturing processes with micro and nanometer capability are continuously developing. Initially emerging as a spin-off from the microelectronics industries, many of these could be classified as planar processes predominantly capable of forming or shaping uniform thin layers. Today there is a growing range of manufacturing processes that have emerged to satisfy the demand for more complex shapes for components having functional features spanning dimensional scales from millimeters to nanometers, sometimes on the same part. Examples include; freeform growth from solids liquids and vapors, rapid prototyping, micro-EDM, water jets, electroforming and imprint lithography to name a few. The goal of this present work is to produce tools and evaluate issues for assembly of micro-scale systems from components manufactured from multiple manufacturing processes.

PRINCIPLE OF OPERATION
A block diagram of the complete micro-robotic assembly system is shown in FIGURE 1. This described system is an extension of collaborative efforts with InSituTec in standing wave based pick and place tools and comprises a three fingered ‘gripper hand’ with self-sensing ‘finger tips’ and optical displacement sensing to measure finger movement. As previously reported, these finger tips comprise carbon fibers of diameter 7 µm and length 3 mm attached to quartz tuning fork resonators that, if energized, can be used to detect contact interactions upon contact with the component surface [1, 2, 3]. Pick and place operation for assembly is achieved with the hand being stationary while the factory floor is translated about a three dimensional cubic volume of length 20 mm using motor driven feedscrews to translate in three orthogonal axes. Assembly is controlled by an operator using a multi-function joystick. This joystick can be toggled to enable motor controls, individually move the fingers in and out and activate oscillation of the finger tips. Two cameras (only one is shown labeled “C” in FIGURE 1) provide visual feedback to the operator. All hardware interfacing (DAQ, camera’s, joystick, function generators), controls and process measurements are implemented using Labview™ software.

The attributes of this new design include:
- Independent displacement and force measurement of each finger.
- Three point measurement of object being manipulated by fingers.
- Independent alignment of each finger for collocating of finger tips.
- Open design to enable real-time imaging using cameras at the top, front, and side of assembly area.
- Automated characterization for replacement of finger tips and the ability to utilize different size fingers.
- Using force sensing, it is possible to provide haptic type feedback for tactile response of gripping action or finger collision.
- It is possible to grip the object with all three probe fingers being excited to minimize finger tip to specimen adhesion.

**GRIPPER HAND DESIGN**

A photograph of the gripper hand and factory floor is shown in **FIGURE 2**. This can be considered to comprise four major components. At the top of the hand three horizontal metal plates can be seen each of which are rotationally symmetric about the central vertical axis with 120 degree pitch. Because the hand hangs downwards, the upper plate of this assembly is the base which supports all components and also provides channels for routing wiring harnesses to two DB9 connectors. Below this base plate is a flexure that supports the three fingers and provides adjustments in four degrees of freedom to enable manual alignment of each finger tip. The lower of these three horizontal plates houses the three vertical alignment screws for adjustment of the fingers as well as serving as the mount for the optical knife edge sensors with another horizontal set of screws for zeroing these sensors. In total, this hand mechanism provides 21 independent alignments.

**FIGURE 2.** Micro-robotic assembly system, photograph showing hand above the moving factory floor (above) plus a solid model of the three fingered hand (below). For scale, the grey disk at the bottom of this lower figure is the size of a US quarter.

**FIGURE 3.** Close up photograph of an individual finger with solid model of finger assembly (below left) and color contour showing displacement of finger about notch hinge (below right).
A photograph of an individual finger is shown in FIGURE 3. Each finger is machined from a monolithic plate of aluminum which comprises a long bar with the standing wave probe mounted at the lower (free) end. The other end of this bar connects to the finger base through a notch type flexure hinge. A horizontally acting piezoelectric actuator is attached to the base plate and contacts the finger a short distance from the flexure hinge. By pushing near to the hinge, the 16 µm range of the actuator results in an amplified motion of around 80 µm at the finger tip (i.e. a lever ratio of ≈ 5:1). Further down the finger from the notch hinge, a knife edge is attached to the finger and this is positioned to bisect the optical path of a photo-interrupter-based, knife edge displacement sensor [4]. This sensor is, in turn, mounted on a slender circuit board that serves as a cantilever flexure to enable manual offset of the sensor.

The probes comprising the finger tips of the hand consist of resonant fiber sensors with a 7 µm diameter carbon fiber attached to one tine of a quartz tuning fork oscillator and have a mechanical resonance of around 32 kHz. These probes have been extensively studied over the last decade and have demonstrated an ability to attenuate problems associated with adhesion forces and provide a sensitive measure of contact between the fiber tip and specimen surface, see [1,2,5]. In this finger design, the modular probes can be easily replaced after which the software is used to run a frequency sweep to determine operating frequencies and amplitudes, see results section.

SENSOR CALibrATIONS
During operation, in addition to camera visualization of the process, there are two voltage based measurement signals to provide feedback to the operator, the sensing signal from the standing wave probe and displacement for the optical sensor. In general, a frequency response curve can be obtained for each fiber using a sine swept function from a function generator to the tuning fork and measuring the amplitude output response. In our software, the frequency response curve can be obtained and algorithms used to obtain the peak amplitude and resonance frequency peak, see [2]. For probe displacement metrology it is necessary to convert the knife edge displacement sensor voltage to a displacement. Calibration of each sensor was carried out by translating the knife edge of each sensor on a linear translation stage monitored using an Optodyne™ laser interferometer. From the measurements it is possible to plot the laser measurement against knife edge sensor output to derive a polynomial expression for this relationship, see FIGURE 4. In practice this displacement occurs at a point on the lever with a considerable offset to the probe tip. Currently, displacement is estimated from this calibration and the lever ratio calculated from the geometry of the finger.

ILLUSTRATIVE ASSEMBLIES
As an example of the pick and place capabilities of this system, FIGURE 5 shows a photograph of an assembly comprising two spheres of approximately 30 µm diameter stacked on top of each other on the edge of a razor blade. Also shown in this figure is the sequence of 6 steps for this assembly. Components are held in place by the naturally occurring adhesion forces between the glass sphere and steel blade in an air environment.

As part of an indentation instrumentation initiative, it is desired to use a surface proximity sensor with nanometer level sensitivity and stability. We are currently exploring the use of a quartz tuning fork oscillator with spheres attached at the free end of the tines to create an interacting surface, for more details see [6]. For symmetry spheres of nominally the same size are glued near to the end of each tine.
FIGURE 6 shows two steps in the assembly process. The tuning fork tines can be seen to the left of these two photographs with a sphere of diameter ≈80 µm being assembled on the upper surface of the top tine. On the right is a horizontal tungsten fiber of 75 µm diameter with a globule of glue at its free end. Prior to attaching the sphere, a small amount of glue is deposited onto the tine with volume being controlled by droplet size and contact time with the tine surface. The sphere that was previously selected from the factory floor is then contacted with the glue adhesion forces of which dominate making it easy to release. In some cases the probe fingers are used to apply pressure to the sphere as the glue cures.

CONCLUSIONS
A system that can be adjusted to meet the demands of different scales of assembly, ranging from millimeter to micrometer size objects. The open architecture enables the system to expand to meet the changing needs of the assembly process. This expansion ranges from using different size tips (and the ability to collocate each tip) to the addition of multiple cameras in different locations to the use of metrology for artifact verification or determination. Performance of the system is shown by the ability to stack micro-sized objects onto the thin tip of a razor blade and the assembly of high resolution proximity probes.

Future work will include the addition of haptic feedback to the user, evaluation of the metrology capability against known artifacts, and addition of a rotary stage to the hand assembly to enable a 4th axis to the process. Because of the scale of the probes it is relatively difficult to align them properly, which becomes more important as the size of handled object decreases. As probe size reduces, visualization will become more difficult and it is speculated that alternative methods involving sensing of known artifacts to determine relative finger tip location will be necessary. There is also ongoing work to determine performance of fingers as a function of excitation frequency and amplitude. As of writing, it is not clear how this can be optimized to enhance control of gripping and releasing objects of different scales.

REFERENCES