INTRODUCTION
This paper will present some observations drawn from our ongoing investigations into the use of standing wave probes for micro-manipulation tools. Generally, a manipulation system will comprise one or more probes that can be maneuvered, like fingers, to pick up and place small components. Such multi-probe devices are often referred to as grippers and/or tweezers. FIGURE 1 is a schematic diagram indicating the major components the tweezers being used to grip a specimen on a substrate. The tweezers is shown in this case as two fibers. The contact forces between components are indicated with the subscripts G referring to the tweezers (fingers 1 or 2) and specimen, S between specimen and substrate and n and t discriminating normal or tangential forces respectively. In this work, the fingers of the tweezers are built from a tuning fork crystal resonator and a 3 mm long 7 µm diameter carbon fiber, see FIGURE 2. Performance and details of operation can be found in [1] while the use of these probes for tweezers applications is discussed in [2].

Over the last two years a number of studies have been undertaken to better understand the issues and develop solutions for assembly of micro-scale systems in ambient environments. Some issues that are addressed by this research and will be presented at the conference include:

- Meniscus dominated, single fiber and specimen interactions.
- Adhesion forces between probe/specimen and specimen/substrate.
- Effects of substrate material, ambient conditions and surface roughness on adhesion forces.
- Two probe tweezer studies for picking and placing glass micro spheres.
- Optimization of probes for grip and release.

Technologies to facilitate micro and nano assembly represent a tool for building structures from individual parts from components manufactured by multiple processes to enable assembly of systems. To achieve this, an assembly system must incorporate many functions such as force sensing, object detection, metrology, manipulation, modification and energy delivery. In the world dominated by

![Figure 1. Block diagram indicating components of a generalized tweezers as part of an assembly tool](image1)

![Figure 2. Images of the standing wave probe. Oscillating fiber (above), oscillating fiber attached to the tuning fork crystal oscillator shown on the right (below).](image2)
intermolecular forces it is not possible to rely on gravity for releasing and holding components in place. Consequently, it is necessary to amass new knowledge of methods for assembly of functional devices.

The aim of current efforts is to develop an automated, multi-axis, micro tweezers station based on standing wave probe ‘fingers’. The self-sensing of these probes will enable force control during pick and place operations as well as dimensional metrology of micrometer and submicrometer features.

EXPERIMENTAL ASSESSMENT
The following sections provide a brief overview of these experimental studies.

Static pull-off force measurements
A series of static pull-off measurements have been performed to determine forces needed to pick up an object from a given substrate and the forces bonding an object to the fiber. Adhesion force between the specimen and substrate was measured by bringing a 150 µm glass sphere that was attached to the probe fiber into contact with a specimen and then retracting the probe until contact was broken, see FIGURE 3. From the displacement of the fiber when the probe was retracted, as well as its geometry and material properties, the force could be calculated using beam bending theory. In other similar experiments force has been measured between a probe fiber and a number of different glass spheres. This work revealed that the substrate adhesion forces could be comparable or greater than those between the fiber and specimen, typically in the range 0.1 to 1 µN. Application of hydrophilic coatings could reduce these forces to levels below our resolution of around 50 nN.

Self-sensing
A key attribute of the probe is that the sensor signal may be used to monitor probe to specimen interactions during manipulation of the micro-scale object. This will be crucial in applications requiring knowledge of what is happening during manipulation as well as detecting when the object has been successfully picked up or released. FIGURE 4 shows the sensor signal from a probe that has a 100 µm glass sphere attached near to its free end using meniscus forces. In experiments, the glass sphere was first attached to the fiber when not energized and therefore not oscillating. The fiber was then excited near to its natural frequency

FIGURE 3. Photographs showing adhesion measurements in which a sphere, attached to the free end of a fiber, is contacted with a substrate and then retracted while monitoring the fiber deflection. In another experiment the fiber is contact directly onto a sphere to measure contact force between the fiber and sphere.

FIGURE 4. Measurements of the release of a 100 µm sphere attached to a carbon fiber by a meniscus film. Upper graph plots the measured magnitude and phase signals from the fiber sensor as the drive amplitude is ramped with the signal jump when object is released. The lower graph shows frequency response of the probe before and after release.
with linearly increasing amplitude and a movie of the subsequent motion recorded simultaneously with the data collection. During these experiments a number of dynamic interactions are often observed. In the experiment represented in FIGURE 5 two rather interesting phenomena were visually observed that also resulted in measurable signal changes. The first of these is motion of the sphere relative to the fiber. This motion could be either along the axis of the probe shank, rotation of the sphere about its own axis (rather like that of a Harlem Globe Trotter spinning a basket ball on his finger) or the sphere rotating about the fiber. Finally, when the amplitude goes above a threshold value the sphere is ejected.

A number of experiments were performed to estimate repeatability of release amplitudes using the same specimen. Again, using a single fiber, the same object was picked up from a surface a number of times relying on adhesion forces. The oscillation amplitude was then increase linearly similar to the previous discussion. Both the magnitude and phase of the probe output were recorded to determine maximum input amplitude needed to release the object. In these early experiments there was considerably variability of the release amplitude mainly because it was not possible to attach the object at the same location along the fiber length. Both phase and amplitude signals can be used to provide a clear measure of the release event. From these measurements, it was possible to determine amplitudes that would result in a high probability of release. It was observed that the natural frequency of the probe would generally increase after release of the sphere.

**Temperature influence on probe resonance**

Using a calibrated temperature chamber, environmental effects on the tuning fork resonator have been assessed. FIGURE 6 shows experiment results from three separate experiments in which the tuning fork was placed in the chamber that was set to -10 degree Celsius and stepped at 1 degree increments. At each temperature the tuning fork frequency response was measured and the value of the frequency at peak amplitude recorded. Deviations from the value recorded at -10 Celsius were then plotted as a function of temperature.

It was found that when tuning fork oscillator is removed from its hermetically sealed environment the resonant frequency can shift by as much as 60 Hz throughout this 30°C range. Again, this is a small extract from a substantially more detailed study. The large temperature variations shown here are reduced if the temperature does not go below that of the dew point. This indicates a significant influence with both temperature and humidity. Interestingly, there is also a small jump of around 2 Hz in the resonant peak at a temperature a little below 0 C for the tuning forks in air. It is thought that this is due to the freezing of thin water films on the tuning fork surface.

**Multi-fiber tweezers**

Multi-fiber probe systems are also likely to find
application in micro and nano assembly processes. FIGURE 7 shows a microscope image of a two fiber probe in which both fibers are attached to a single resonator beam. This indicates just one of many concepts that are currently being manufactured and characterized. In this example it is possible to use one tuning fork crystal oscillator with two fibers attached and a probe second with one fiber to create a 3-point gripper. Clearly, many combinations of such an approach are possible, many of which are currently being studied.

Finally, a semi-automated gripper station has been built to investigate micro-manipulation and assembly techniques using two probes that can be moved towards and away from each other to create a tweezeing action. Objects ranging in size from 10 to 200 µm have successfully picked up and released using standing waves, see FIGURE 8. This system can be operated using joysticks that operate both the tweezers and a three axis motion control stage. Currently, feedback is provided by two high magnification, long range objective camera systems. This system has also been used for simple assemblies.

FUTURE WORK
Different design concepts including three and more finger grippers to be able to pick submicron object as well as larger up to around 500 µm are to be implemented in the near future. In the longer term a complete robotic system capable of automatic assembly based on known position of assembly parts and with ability to find needed parts at unknown position (vision system with shape recognition) will be built and tested. This system will also be equipped with force sensing technology as well as functions making this tweezeers system a full dimensional metrology machine (micro CMM). Finally, there is a substantial ongoing effort to design and manufacture probes with reduced dimensional

scales operating at higher frequencies. A times ten per year scaling and frequency increase is the goal of this sub-program.

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