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Micro/macro force-servoed gripper for precision photonics assembly and analysis

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SUMMARY

Photonics is a field that straddles both the macro and micro worlds. It largely deals with macro-scale devices, but many of these require sub-micron-scale precision in assembly. This makes it a very interesting application domain. We describe a microgripper for microassembly of photonic devices and micro-exploration of the properties of sub-micron attachment means (such as solder and UV epoxy). The microgripper has multi-degree-of-freedom actuation and a unique micro/macro actuator on the gripping axis to facilitate human loading and unloading and also very precise accommodation. We demonstrate the force sensitivity and stiffness of approximately 20 mN and 70 mN/um, respectively to be sufficient for the intended tasks. Finally, we demonstrate the gripper accommodating forces of a large solder ball freezing and cooling as a prelude to our intended study of sub-millimeter solder balls in sub-second heating regimes.

KEYWORDS: Microgripper, Photonics assembly, Force servoed.

1. INTRODUCTION

Photonics assembly presents an interesting field of study for researchers interested in nanotechnology. It bridges the gap between the nano world and the macro world. The components of a typical photonic assembly – optical fibers, photodiodes, laser diodes, lenses – are millimeters in size, yet, in many applications, they require positioning accuracy on the order of tens to hundreds of nanometers. Because of the precision required, most high-precision photonic devices are painstakingly assembled by hand under microscopes, with little aid from automation.[1,2] This may seem counterintuitive; humans have hand tremor and poor fine motor control at the level of a millimeter or significant fractions thereof. Machines, on the other hand, can easily be made quite precise. So, why hasn't automation dominated this field?

The advantage humans have is adaptability across many degrees of freedom. At sub-micron scales, everything is subject to change. Tiny changes in temperature can cause significant deformations due to material coefficients of thermal expansion. (For example, a four-centimeter long piece of aluminum will grow about one micron every degree Celsius). Non-linearities caused by friction and backlash change with time and environmental conditions. But most important, conventional attachment means (solders, UV epoxies, and weldments) are unpredictable below a few microns.[3–5] This unpredictability of bulk materials can cause undesired shifts in up to six dimensions, hence the need for the high degree of flexibility that human operators provide.

2. PHOTONICS PRECISION

There are two major realms of precision in photonics assembly: that of single-mode optical fiber, and that of multi-mode optical fiber. Multi-mode is used for short-haul communications in which transmitted power is not that critical. Multi-mode fiber is characterized by core diameters in the hundreds of microns, so it is easy to align them with respect to each other and with respect to other active and passive optical devices. Single-mode fiber, on the other hand, is aimed at long-haul networks where power efficiency is of prime importance. Single mode fiber is characterized by core diameters around 10 microns or less with insertion loss (efficiency of connections) below 0.1 dB. To achieve this, a simple fiber-to-fiber coupling must be aligned to within 0.6 microns. In order to avoid tolerance stack-ups in an overall error budget, it is generally necessary to maintain alignment of individual components to 0.1 – 0.2 microns for this type of simple assembly.

3. ADVANCED MANUFACTURING STRATEGIES

Although the photonics industry is in an economic slump, the current state of manufacturing technology is unacceptable. Using manual labor under tedious conditions results in typical assembly times of hours for devices of modest complexity compared to minutes or seconds for electronic devices of similar complexity. In fact, the state of photonics manufacturing is similar to the state of electronics manufacturing in the early 1970's: hand-assembled components connected point-to-point with a soldering iron. (A fusion splicer replaces the soldering iron in photonics.)

Several advanced approaches to photonics manufacturing have been proposed that make use of "silicon optical benches."[6] A particularly novel variant called *Surface Mount Optics*[7,8] has been proposed by CyberOptics Inc. (formerly Avanti Optics Corp.) that uses pre-aligned components that self-align onto a silicon optical bench. Like an electronic circuit board, these components can be cheaply and rapidly

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assembled with conventional pick-and-place manufacturing equipment used by the electronics industry.

Although the attachment means is not specified in reference [8], solder, UV epoxy, and weldments are commonly used in photonics assemblies. It is the predictability and repeatability of these methods of attachment that we plan to study with the described microassembly station.

3.1. Precision attachment

The photonics industry relies on three major methods of precision attach: soldering, ultra violet (UV) epoxies, and welding. While all have been under extensive development for years or decades, none of these approaches can produce one-shot attachments with greater precision than a few microns.[1,4]

3.1.1. Solder. Solders have been around for millennia and the basis for accurate, self-aligning flip-chip manufacture (IBM's C4 process) has been around for decades.[9] Soldering involves the "wetting" of a molten metal alloy over another. It is the wetting action and surface tension that give solder its amazing self-alignment capability. Flip chip assembly can tolerate misalignments approaching 50% and still "pull-in."

During this process, intermetallic compounds rapidly form, which form the basis of the bond. However, these intermetallics are essentially compounds in solution and they form grains and layers of chemically different materials. These grain boundaries are constantly evolving at a rate proportional to time and temperature and they result in weaknesses – "fracture lines" – in the material. Because the soldering process is so dependent on time and temperature, extensive study has been performed on the behavior of solders. However, do to economic opportunity, nearly all the research on solders has focused on the electronics industry. This industry typically uses solder reflow ovens that slowly ramp temperatures up and down at controlled rates over several minutes. And precision attachment is defined by the proper electrical attachment of corresponding pads. Electrons are very forgiving of misalignments on the order of many microns. A few researchers have studied solder down to a few microns (e.g. reference [4]) over cycle times of as short as tens of seconds.[5] No published literature has appeared on the subject of sub-second cycle times.

3.1.2. UV-Cure Epoxy. UV Epoxies are very commonly used in photonics assembly[10] and in microassembly.[11] The idea behind UV-cured epoxy is light is used as a catalyst to initiate the chemical reaction that causes it to "set". The epoxy is one-part, and is applied in a liquid or gel state. With the application of ultraviolet light, the epoxy cures to its fully hardened state with no mixing or additional mess. They are relatively quick (on the order of seconds to minutes), relatively safe, and there are a variety of formulations for many needs.

The curing process involves cross-linking and chaining of the molecules that make up the epoxy. As the molecules rearrange themselves, movement occurs. Often, binders and volatiles also appear in epoxies that may disperse during the curing phase. These phenomena result in shrinkage on cure. Some epoxies are touted as "no-shrink" or "low-shrink". Often, these epoxies merely contain solids as fillers that do not shrink. This type of contamination is unacceptable for precision microassembly.

Epoxies, which are thermoset polymers, do not melt when heated (as opposed to thermoplastics). However, all epoxies have a "glass transition region" through which they undergo a transition from a rigid state to an elastic state after they have cured. The two states are characterized by different coefficients of thermal expansion and the thermal behavior inside the glass transition region can be nonlinear.

A particular problem with epoxies is they out-gas and can fog optical elements over time.

3.1.3. Welding. Welding is a particularly violent process that, surprisingly, is often used in delicate photonics assembly. The reason it is so commonly used, despite the fact it is difficult to control, is its long-term stability, particularly with annealing to reduce the initial residual stress. Welding in photonics assembly is typically done with very short electrical or optical (intense laser light) pulses. It is a very powerful process that causes unpredictable misalignment of the parts during initial attachment. However, it does not out-gas, it is very stable, and it can be used on a large variety of benign and beneficial materials. The most common way to employ welding in a photonic assembly is through the use of a metal clip to hold the parts that can also be "laser-hammered" into final shape by lower-power blasts after the initial shock of bulk weldment.

3.2. Dealing with movement

Regardless of the attachment means in microassembly, relative movement of the parts will occur during the "lock-in" mechanism of the means (freezing, curing, or fusing). This movement is generally on the order of a few microns, is highly unpredictable, and results in a random misalignment regardless of how carefully the parts are aligned before attachment. Since this movement will occur, there are only three broad approaches to dealing with it: resisting the movement, releasing the parts, or accommodating the movement as it occurs.

3.2.1. Resisting Movement (Holding Still). There is a strong temptation to resist movement. In creating precise positioning and alignment systems, a common goal is to make the structure very stiff. In fact, with most multi-degree-of-freedom systems, high stiffness is tantamount to high precision because varying loads caused by varying joint configurations cause varying deflections (error). Given a stiff structure, it should be easy to resist the movement.

But what constitutes "stiff"? Consider a solder ball attachment means similar to a silicon flip-chip assembly mechanism as shown in Figure 1. (A real flip-chip assembly would involve dozens of such balls, but all would behave the same.) This can be any type of assembly with any type of solder alloy, but the basic purpose is to precisely assemble part A to part B. If we assume eutectic tin-lead solder (63% Sn, 37% Pb – not a particularly good structural solder, but one that is familiar to all) it must be raised above the melting point of 183 °C to wet to the upper and lower surfaces. Upon wetting and proper intermetallic formation, the solder can be

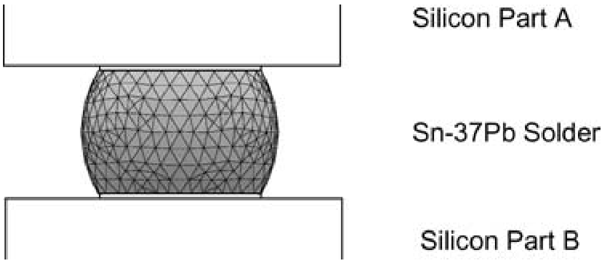

Fig. 1. Solder ball attachment of metallized silicon pieces. (Resulting solder shape simulated with *Surface Evolver*.[10])

cooled to solidify. At 183 °C, the solder freezes to become a solid and the assembly is now a rigid structure. However, the rigid structure is approximately 160 °C above room temperature and must be further cooled.

Nearly all materials have a positive coefficient of thermal expansion, which means they shrink when cooled. Sn-37Pb solder has a coefficient of thermal expansion of 24×10^{-6} per degree C that is constant throughout this temperature range. In cooling from 183 °C to 23 °C, a 250 micron tall ball of solder will shrink about 1 micron in height. Because this is a physical property of the material, resisting it requires stretching the material according to its Young's modulus of 39.6 GPa. For a single solder ball of 300-micron diameter, 11 Newtons would be required! Fortunately, this exceeds the yield strength of the solder, which is more than three orders of magnitude lower. At around 8 milliNewtons per ball, the solder will begin to plastically deform. We can compute a fixture stiffness if we assume we need to maintain this force over a distance appreciably less than the 1 micron of shrink. For a 10% error tolerance, 8 milliNewtons over 100 nanometers is 8×10^4 N/m per solder ball.

Plastic deformation is desired because if the solder does not plastically deform, it will spring back to its rest state as soon as the fixture is released. This would nullify the effect of resisting the movement. However, plastic deformation is harmful to long-term stability because it results in built-in stresses that will relax (and move) over time. Clearly, resisting the movement is not a good option. Not only does the required stiffness become unachievable with a small number of solder balls (or equivalent solder area or epoxy bonds or whatever), but the resulting built-in stress will likely result in performance degradation and early-life failure.

Annealing was mentioned above with regard to welding. Annealing is the process of relaxing internal stress by allowing material to redistribute itself, usually through heating. This is often used in welding processes to reduce stress and deformation caused by the violent heating of the parts once they are rigidly attached. Given particular properties of the attachment material, it is possible to imagine rigidly resisting the movement of the parts while not inducing plastic deformation. Subsequently annealing the material in that rigid configuration would then relieve the stress, allowing the parts to maintain their precise alignment without plastic deformation and without "springing back" to the unstretched state.

The unique properties of the material that permit this can be quantified by noting that the yield strength, σ_y, must be greater than the product of the thermal expansion of the material and its Young's modulus, E:

$$\sigma_y > E c_{TE} \Delta T$$

where c_{TE} is the coefficient of thermal expansion of the material and ΔT is the difference between the melting point of the material and room temperature. If the yield strength is less than this, the material will plastically deform, by definition. As an example, high carbon spring steel has a yield strength about one third that required to achieve non-plastic deformation, not to mention that completely eliminating all residual stress through annealing is not possible.

3.2.2. Release the Part. The opposite extreme is releasing the part to provide no resistance to the movement at all. If it is known that movement will occur, a designer can take the movement into account during part alignment. This pre-supposes two things: the instant the assembly becomes rigid can be known and the movement of the attachment means can be accurately predicted. Both of these are questionable.

In the solder ball example above, one could envision accurate temperature controls that permit releasing the part at, say, 182 C. But there are other mechanisms involved in the movement (not to mention a much less controllable method for UV-cured epoxies). For example, there is shrinkage associated with the change of state (from liquid to solid). Also, it is unlikely that uniform cooling can be achieved. Thermal gradients from the inside to the outside will cause the outside to freeze first, potentially leading to micro-voids and asymmetries deep within the structure. These voids and asymmetries will likely result in chaotic and unpredictable movement during cooling. Also, slight differences in cooling from one side to the other can also result in unpredictable movement. Finally, oxide formation is very aggressive at elevated temperatures. Oxides generally have much different physical properties than the native materials and even in the presence of flux can induce structural asymmetries leading to unpredictable movement at the nano-scale.

3.2.3. Accommodate. The third options takes the middle ground. Neither completely constraining nor completely freeing the parts, accommodation implies adjusting the process in real-time to conform to some reference behavior. Accommodation can be achieved either actively or passively and usually takes for the form of partial constraints. For example, in the case of solder, one might constrain lateral movement while allowing free movement vertically. This can be achieved either passively with a carefully designed flexure, or actively with a force-servoed manipulator. In either case, the goal is to force the process to conform to some idealized behavior, such as an ideal thermal contraction model.

4. MICRO/MACRO GRIPPER DESIGN

We believe, based on our own unpublished experiments and the published works of others, that just "letting go" does not provide the ultimate precision required by many applications. Furthermore, passive flexures do not have suitable re-programmability and, at a minimum, actuating the gripping action is necessary for convenience across large numbers of experimental trials. Therefore, we embarked on the design of a compact, active, multi-degree-of-freedom, force-servoed gripper.

We want a fairly flexible design that is useful for a number of different research projects on microassembly, yet could also be installed in prototype manufacturing equipment. To study the behavior of solders and epoxies at both low speed and high speed conditions of attachment, we designed a novel, dual-actuation gripper with both macro and micro actuation. Macro actuation is necessary in the grip axis to accommodate a variety of different macro-scale parts and to facilitate human loading and unloading. Micro actuation is necessary to achieve sub-micron reactivity to the precision processes involved. These capabilities are combined into a single, compact device in order to provide stiff, multi-degree-of-freedom actuation as end-of-arm tooling.

Others have embarked on such projects. Orthotweezers[13] is a novel approach to force-based dextrous gripping and microassembly with similar goals. However, Orthotweezers are slow, bulky and not suited to medium speed or end-of-arm tooling, which is a consideration for this project. It is also not clear how large a force they can apply. The main use of Orthotweezers has been dextrous assembly of small parts that are UV glued in place (or held with wax) using very light assembly forces. Another similar approach is the Chopstick manipulator of Sakai et al.[14] Their use of piezo actuators is very similar in form to that ours, but they, too, have thin, flimsy fingers that are not suitable for exerting significant forces. Because the forces of solder can be large, stiffness is important. Furthermore, Sakai et al have made no attempt to introduce force sensing and their device has few degrees of freedom. This will lead to stack-up errors as they add serial chains of positioners with finite stiffnesses as an afterthought, rather than designing in the multiple degrees of freedom eventually desired. Finally, Hofmann et al[15] and Tanikawa et al[16] have developed modular microgrippers or microgripper attachments for miniature machining stations. These have high stiffness and are designed to exert significant forces, but they are low degree of freedom and not well suited to this scale of precision.

Our approach is novel because it combines macro and micro actuation, where beneficial, into a single device and strives to combine many precise degrees of freedom in a stiff, compact package that is appropriate for high-precision positioning and force control.

We should point out the ongoing efforts to make six-degree-of-freedom robotic platforms with sub-micron precision for photonic assembly. Many commercial manufacturers are claiming multi-axis stage systems with deep sub-micron repeatability. After evaluating many of these devices, we have learned the claims are always based on the performance of a single axis, which can be quite good. However, manufacturers underestimate the difficulties encountered when stacking up errors with serial chains. One exception is the hexapod device from Polytec PI.[17] This device can reliably achieve six-degree-of-freedom repeatability to around 300 nm. A 6-DoF research effort also claims precision to below 500 nm,[18] but their published claims are difficult to scrutinize.

4.1. Micro/Macro actuation

Macro actuation is only required in the gripping degree of freedom. Gross translational motion can be accomplished by making the gripper small and stiff and mounting it on a gross motion platform of lower precision (providing it can be "locked down" to avoid servo errors). After considering several candidate designs, we settled on the three-degree-of-freedom mechanism illustrated schematically in Figure 2. One degree of freedom is lead-screw-based and provides simultaneous opening and closing of the gripper fingers with up to several millimeters of travel. The gross actuation is effected by sliding the asymmetrically shaped wedge in and out along precision pins, forcing the back ends of the gripper levers apart or together. A 5 mm Smoovy motor inside the wedge provides the motive power. In this mode, the fingers pivot on the flexure hinges.

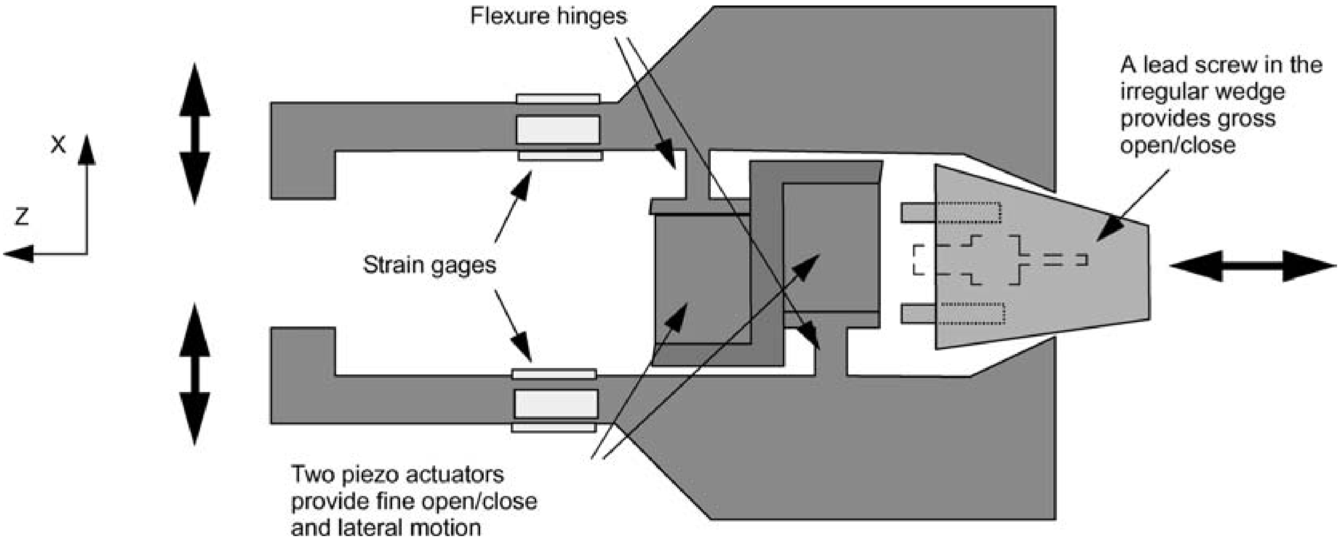

Fig. 2. Schematic drawing of the micro/macro actuation of the gripping degree of freedom. Three actuators provide gross/fine opening and closing of the tips plus lateral motion.

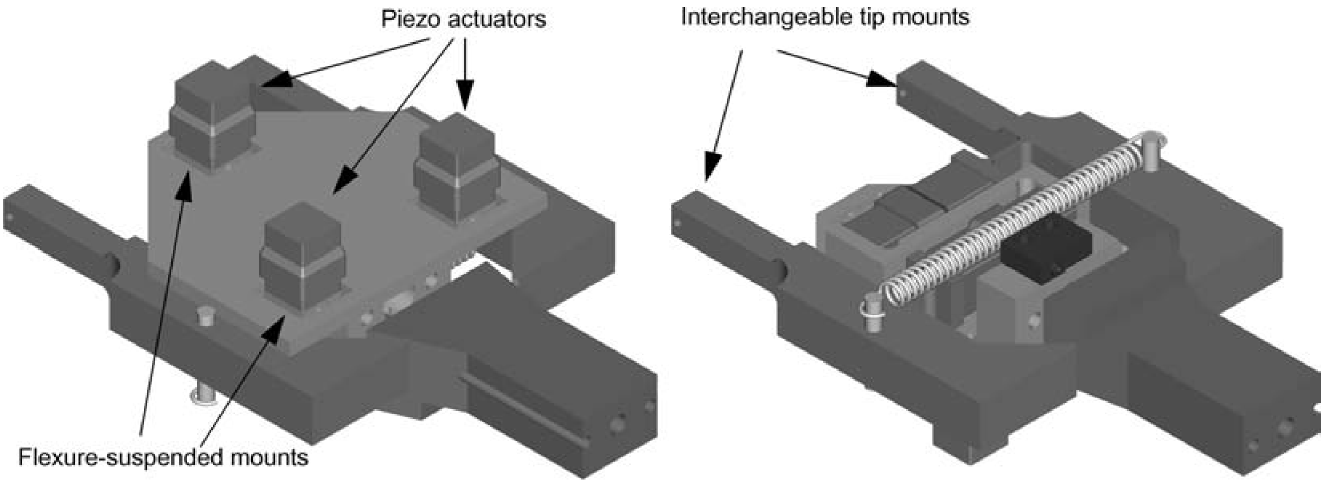

Fig. 3. Bottom and top cad views of the micro/macro gripper.

For fine actuation, two piezo actuators from Polytec PI independently control the positions of each gripper finger. They operate through the flexure hinges, using the wedge as a fixed fulcrum. For compactness and maximum stiffness (given the configuration), the two piezos are placed parallel to each other. This results in unequal lever arms, which is the reason for the asymmetric wedge shape. The two different surfaces of the wedge actuate the fulcrums at different rates, which cause the tips to move at the same rate through the different lever arms.

To achieve stiff, out-of-plane, fine motion, a tripod of piezo actuators is attached to the backside of the mounting plate. These actuators, which ride on torsional-flexure mounts milled into the base plate, provide translation in the Y axis, rotation about the Z axis (roll) and limited rotation about the X axis (fig. 3).

4.2. *Force sensors*

The most important aspect of the gripper is the embedded force sensors. As indicated in Figure 2, each gripper finger is instrumented with semiconductor strain gages for measuring forces in two axes on each finger. These are critical because it is the sensing that allows this gripper to modify its behavior and become a truly programmable test fixture.

The sensors operate as conventional cantilever beams. While it is possible to extract many degrees of freedom of force sensing from a single cantilever beam[19] (in fact, it is possible to extract all six degrees of freedom),[20] we chose to measure only the two orthogonal values. Accurate multi-axis sensing requires a circular cross-section, but the square cross-section has slightly greater torsional stiffness. Using the standard beam equations:

$$K = \frac{3EI}{l^3} = \frac{3Eba^3}{12l^3}$$

where K is the stiffness, E is Young's modulus of the material (aluminum in our case), I is the moment of cross-section (for a square cross section, $a = b$), and l is the length, we choose design dimensions such that the flexures provide a stiffness of 1050 mN/um. After fabrication, we measured and tested one of the finger sensors. Based on the as-built dimensions, we predict the beam has a stiffness of 840 mN/um. To test this, we firmly clamp the finger in a rigid fixture and measure the deflection of the beam tip with a precision capacitive displacement transducer. These measurements indicate a stiffness of 375 mN/um for a single fingertip. While this is surprisingly different from the as-built predictions, the overall system stiffness is of more interest, which we'll investigate in the next section.

The sensing electronics consists of a standard Wheatstone half-bridge with constant excitation (no synchronous demodulation). The signal is then amplified with an instrumentation amplifier.

We use the *Shape from Motion Calibration* technique[21] to extract calibration parameters of the fingertip sensors. This is an extraordinary technique for reducing the burden of multi-axis sensor calibration. It does not rely on known applied forces, as is common with typical least squares techniques. Instead, a mass is held in the gripper and the gripper is randomly reoriented in space to apply a large number of unknown (but constant magnitude) loads. Single value decomposition simultaneously extracts the calibration matrix and the set of load vectors that were applied to the sensor.

The fabricated gripper is shown in Figure 4. Exchangeable tips attach to the ends of the cantilever beams to accommodate different types of parts.

5. EXPERIMENTS

To verify operation and characteristics of the gripper mechanism, we mounted it directly to a three-axis Piezosystem/Jena stage without the tripod of piezo actuators. This will provide a measure of the stiffness of the assembled mechanism, which is difficult to predict, without corruption from the piezos. To track endpoint motion, we attached an optical fiber (SMF-28 long haul, single mode fiber) to the object being gripped and focused a video microscope with a 50x Mitutoyo objective onto the cleaved fiber end. Illuminating the fiber produces a bright spot on a dark

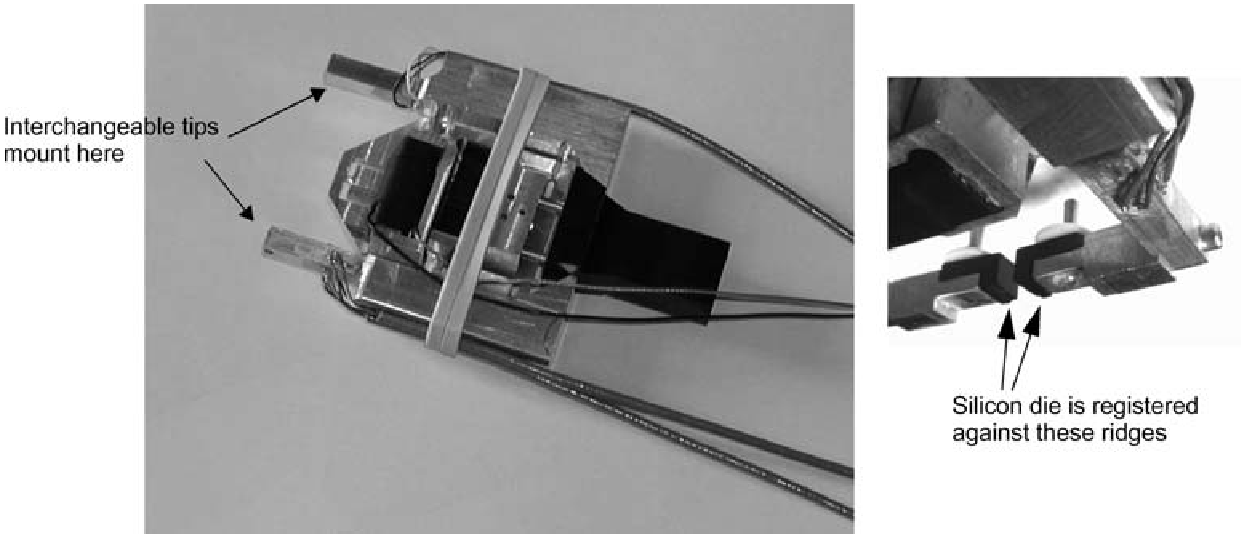

Fig. 4. The fabricated micro/macro gripper. Overall dimensions are approximately 50 mm wide by 75 mm long. The inset shows the mounting of the silicon tips.

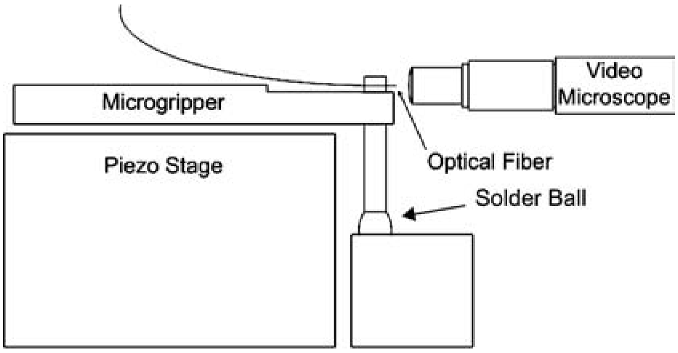

Fig. 5. Experimental apparatus with 3-axis piezo stage and spot tracking.

background that is easily extracted using binary thresholding and centroid finding. With a Sony XC-55 progressive-scan camera, we can reliably achieve relative sub-pixel tracking to a noise floor of about 0.15 microns at 30 Hz. (This is largely due to vibrations coupled through our poorly-isolated optical bench.) The accuracy of the spot tracker was verified with a precision mechanical stage with an optical fiber glued to it. Drift is minimal over the length of our experiments (fig. 5).

5.1. *Spot tracking*

Using the spot tracker, we first examined the motion of the gripper fingers over several open/close cycles. The end point trajectories appear in Figure 6. Because these motions were created by applying the same voltage, we expect the right finger to move less as it has a lower mechanical advantage. The left finger exhibits non-negligible hysteresis, which could induce roll motion to a device being manipulated laterally. This has no effect on our current experiments, so we will investigate this at a future time using two optical fibers and dual-spot tracking.

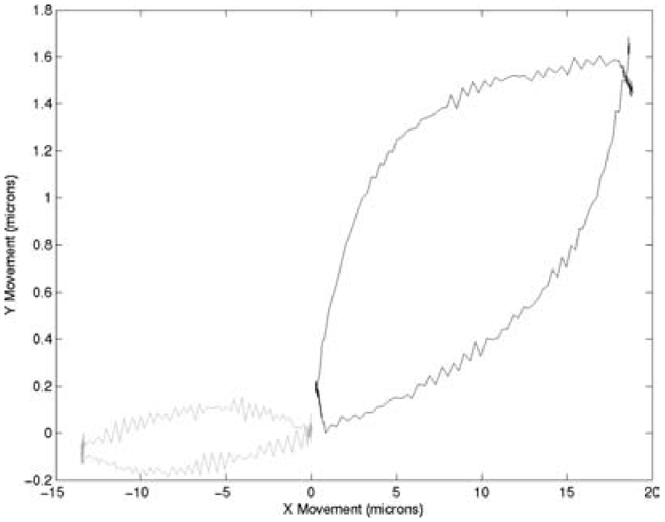

Fig. 6. Relative movement of the left and right fingertips during free gripping motions. (Left finger is on the right from the spot tracker vantage point.).

By applying known loads, we simultaneously extracted calibration parameters and stiffness measurements of the entire mechanism. The complete apparatus had a tip stiffness during gripping of 36.8 mN/um. However, by replacing the gripper assembly with a rigid bar of the same length, we determined the piezo stage contributed roughly 50% of the deflection. This stage will ultimately be replaced by the stiffer piezo actuators, so the actual stiffness value of the gripper assembly is 69.4 mN/um. Meanwhile, the sensitivity floor of the force sensors due to noise and hysteresis is currently below 20 mN, or about a quarter micron, and we expect to push that down further with a new signal conditioning circuit.

5.2. *Solder heating*

One of the primary end uses of this gripper is to study the behavior of solders and UV epoxies in a variety of situations. Ultimately, we plan to observe solder behavior during reflow cycles as short as several milliseconds, using vapor-deposited surface micromachined heaters with very little thermal mass. A study on this scale has never been

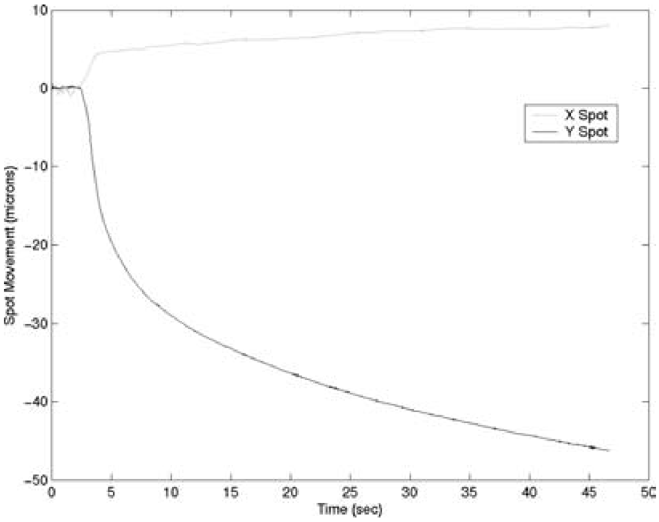

Fig. 7. Motion of the spot in X and Y as the solder cools with no active force accommodation.

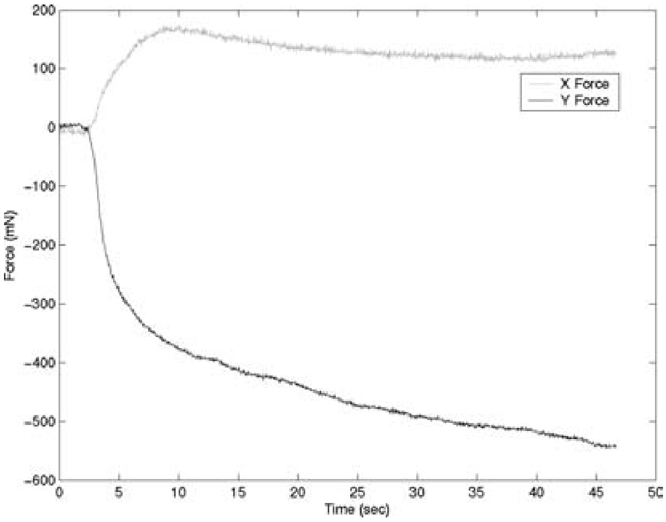

Fig. 8. Force response of the first trial. The only force accommodation is passive flexing of the structure.

published, to our knowledge. Although the sampling rate on our force sensors can be pushed up into the thousands of Hertz, the sampling rate of the spot tracking camera is only 30 Hz. At this rate, the spot tracker is only good for verifying start and stop locations and tracking drift over time. For the set of experiments reported in this paper, we use a large solder ball and bulk heating to extend the time of the cooling operation in order to study the correlation of the two sensors at the 30 Hz rate.

We use a single solder ball of several millimeters for these verification tests. The advantage is convenience and the avoidance of special test parts, but the disadvantages are large heat input and large-scale motion. The large heat input will certainly push the test out of the adiabatic regime in which heat only goes into the part. Instead, significant heat will certainly be lost to the surroundings. This will cause thermal expansion and contraction of the fixture as well as the solder. With a solder ball a few millimeters in size, we can expect thermal expansion in the range of tens of microns.

Our first experiment involves no force accommodation at all. Instead, as the solder cools, the gripper and stage stay put, within the limits of their mechanical stiffnesses. From Figure 7, it is clear that the gripped object is moving quite a bit in the -Y direction. It is being pulled down by the cooling solder (and other parts of the fixture that absorbed heat). The forces involved are plotted in Figure 8. There is a low-gain visual servoing control loop on the x-position in all experiments in order to lightly constrain the spot to vertical movement. The actuation is weak, as Figure 7 shows the spot moves nearly ten microns in the x-direction. However, the effect of visual servoing can be seen in Figure 8 as the x-force first increases, then slowly decreases until the integrator limit is reached, at which point it levels out. Beyond 40 seconds, the change is likely caused by relaxation in the exaggerated solder blob (perhaps with some contribution from drift).

Note both the force and spot plots start out flat. This is almost certainly the molten state. The solder is cooling, but it hasn’t frozen, yet. Once solder has frozen, it immediately starts contractingand pulling down on the device. However, there appears to be a brief interval during which the slopes of both Y Spot and Y Force are less aggressive. We hypothesize the first few seconds are marked by internal pockets of liquid solder that has not frozen, yet. Therefore, it does not contribute to the tugging on the gripper. After that brief interval has elapsed, the decay seems to be a regular exponential (fig. 9).

This may be verifiable with localized heating. We have used deposited resistive heaters before to measure the temperature of the heater to estimate the freezing point of solder.

To accommodate the force, we simply employed an integrator on the force error signal, with no feedforward term. There is anti-windup protection to keep the integrator from growing without bound and there is a threshold to prevent noise from causing hunting near zero. From the force plot in Figure 10 the lag of the integrator is apparent as is the noise threshold, which is set at about 30 mN. Again, from the spot plot, the interval of hypothesized molten core is still visible at the top of the slope.

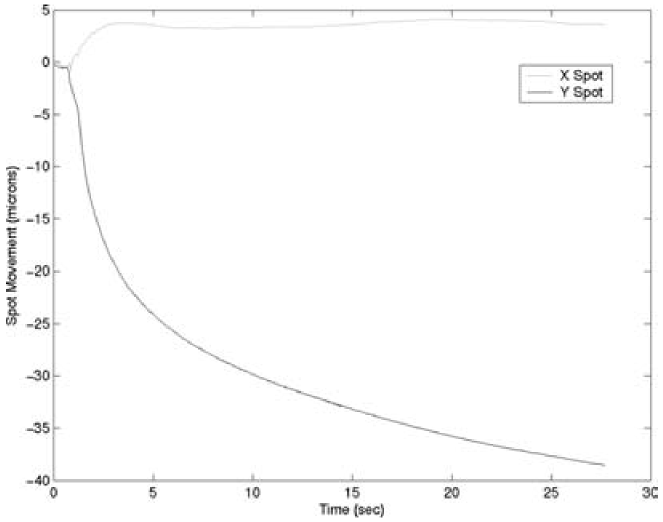

Fig. 9. Spot motion with force accommodation turned on.

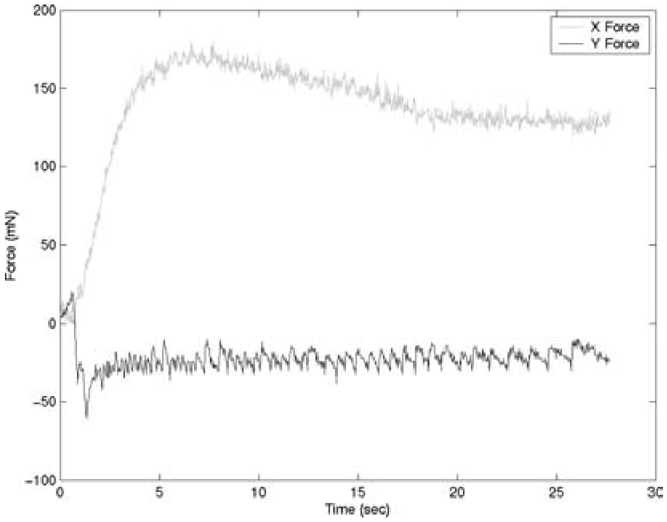

Fig. 10. Force response in X and Y with Y force control turned on.

We should point out that the amount of heat put into the solder ball was not controlled, so it is not instructive to compare the amount of motion from trial to trial.

6. DISCUSSION

We described the characteristics of the photonics industry that make it attractive for entry-level nanotechnology exploration. Because it spans the macro, micro, and nano realms, it provides many rich opportunities of study, yet is still very familiar. It is characterized by precision in the tens to hundreds of nanometers with devices that are on the order of millimeters.

We also described a novel macro/micro gripper with multiple degrees of freedom for photonics assembly and analysis. The gripper has macro actuation to facilitate human loading and unloading of parts, but it also provides micro actuation to precisely position the part during active alignment and active accommodation. The primary goal is to provide a highly reconfigurable device for the study of solder behavior at very quick bonding speeds.

We demonstrated the force sensors were sensitive enough and stiff enough to maintain force-controlled precision to less than half a micron. We also demonstrated the gripper accommodating a large solder ball undergoing heating and cooling cycles.

In order to truly exercise the capabilities of the microgripper, we intend to demonstrate very small solder balls (less than 300 microns in diameter) heating and cooling above localized heaters in several milliseconds. We have already demonstrated it is possible to form bonds under these conditions, but we need to more fully explore the behavior of solder in this realm.

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