Manufacturing of a Hybrid Acoustic Transmitter Using an Advanced Microassembly System

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Abstract—Advances in both capabilities and miniaturization of medical devices offer promising prospects for medical treatments. Applications range from simple diagnosis to complex treatment tools. Miniature untethered robotic devices are playing a central role within this growing trend, and devices are becoming available on the market. However, one of the biggest challenges is the localization of these devices within the human body in order to close the control loop. This paper presents the design and fabrication of a novel device for localization based on acoustic transducers. The individual microfabricated MEMS components are assembled using a state-of-the-art 6-DOF micromanipulation system in order to meet the high-precision requirements. First position determination experiments have successfully proven the concept with results on the order of submillimeters.

Index Terms—Acoustic tracking, hybrid MEMS, microassembly, ultrasound.

I. INTRODUCTION

THERE IS a clear trend toward the miniaturization of medical devices for minimally invasive medical procedures, ranging from diagnosis, and targeted drug delivery to complex surgical interventions. One commercially successful device is the M2A capsule endoscope introduced by GIVEN IMAGING in 2001—a camera pill with a length of 26 mm and diameter of 11 mm that is swallowed and delivers images as it moves through the gastrointestinal tract. Its essentially noninvasive nature allows for less painful diagnosis than traditional endoscopy, as well as imaging of the small intestine, which is impossible with conventional endoscopes. A large number of devices from other companies have since appeared on the market making the capsule endoscopy market a multimillion-dollar business. For the state of the art in capsule endoscopy research, see [1].

The accurate localization of the capsule during its motion through the gastrointestinal tract remains challenging. Methods include the measurement of the dc magnetic field of a permanent magnet mounted inside the capsule [2], [3] or extracting position information from the RF signal used for sending images [4]—the spatial resolution of both methods being in the range of centimeters. The drawbacks are that in case of the first method a relatively large magnet is needed for a good signal, since the magnetic field is proportional to its volume. On the other hand, the RF method demands complex and time-consuming algorithms.

We recently presented an algorithm to accurately determine the location of an ultrasound source within heterogeneous media such as the human body [5]. Experimental results have shown submillimeter accuracy and the potential for localizing capsule endoscopes equipped with ultrasonic emitters. State-of-the-art ultrasonic emitters include piezoelectric crystals, which are excited by a harmonic voltage of up to several hundred volts, or microelectromechanical (MEMS) devices, that still require a driving voltage of up to 100 V [6], in addition to the wiring and energy storage inside the capsule.

Together with increasing complexity and miniaturization of capsule devices, manufacturing and assembly processes are becoming crucial elements. In this paper, we present the use of an advanced 6-DOF microassembly system for high-precision assembly and mechanical testing of the individual components of novel miniature acoustic devices (see Fig. 1).

II. ACOUSTICS AND ACOUSTIC TRACKING

A. Overview

Minimally invasive surgical localization comes in many forms, such as endoscopy, magnetic resonance, computed
tomography, positron emission tomography, and ultrasound. For the localization in human soft tissue, only ultrasound among these techniques combines good resolution, minimal adverse health effects, high speed, adequate frame rates, and low cost [7].

The localization of an acoustic transmitter can be performed by spatially separated receivers combined into an array. The transmitter location relative to the receiver locations can then be calculated by estimating the Time Difference Of Arrival (TDOA) for different receiver pairs. We performed simulations for varying receiver arrangements assuming that a signal can be detected independent of the distance between transmitter and receiver [8].

For a given TDOA, the transmitter location can be found from the intersection of several hyperbolic areas. As a result, probability maps for the transmitter locations are obtained, as shown in Fig. 2. The grayscale image represents the probability values between 0 (black, low probabilities) and 1 (white, high probabilities) for the corresponding points in the $z = 0$ plane. The simulation uses an inverse approach to the synthetic aperture focusing technique to find probability maps for an emitter location if the receiver arrangement is given. With this method, the resolution and accuracy of the emitter localization can be estimated. It showed that the probability distribution depends on the receiver arrangement, in addition to the frequency of the emission. The regions with the highest probability for the transmitter location diverge (rather wide white lobes) with distance from the receivers and converge (narrower lobes) with higher frequencies and if the two receivers are further apart from each other.

It is found that the resolution reaches a constant level for distances $d \geq 30\lambda$ between the receivers, where $\lambda$ is the wavelength of the emitted signal. If the three receivers are in a distance of $d = 30\lambda \approx 15$ cm at a frequency of 300 kHz, the expected resolution is less than 1 mm.

B. Wireless Acoustic Transmitters

A wireless acoustic transmitter is a mechanical device that is externally excited by some type of force and reacts with the emission of sound waves. The activation energy can, for example, consist of a magnetic field generated by an electric coil (see Fig. 3). The feasibility of such a wireless resonant magnetic microactuator has already been demonstrated within the scope of the MAGMITE microrobotic system [9], [10]. The core component of these agents is a magnetomechanical transducer that harvests the energy of an oscillating magnetic field and directly transforms it into mechanical motion. These devices gain importance for biomicro robotic applications since they can be used for data transmission or localization purposes. A custom acoustic transmitter prototype module has been designed and manufactured, and basically consists of three components, as shown in Fig. 4. The base structure is made out of a 20-$\mu$m-thick gold and contains a centered $1.0 \times 1.0 \times 0.05$-mm nickel body. The top element is also made out of a 20-$\mu$m-thick complex gold structure consisting of two beam springs holding a $1.0 \times 1.0 \times 0.05$-mm nickel square in the center. Both elements are separated by a 110–300-$\mu$m-thick rectangular plastic spacer. Once assembled, the two nickel bodies have a clearance of 10–200 $\mu$m, depending on the thickness of the plastic spacer. Both gold and nickel structures are manufactured by means of electrodeposition as illustrated in detail in the following section.

Fig. 2. Probability distribution for a transmitter at location $x = -6\lambda$ and $y = \frac{4\lambda}{3}$, where $\lambda$ is the wavelength of the emitted signal.

Fig. 3. Operating principle of an ultrasound transmitter. An oscillating magnetic field, e.g., generated by a coil $C$, mechanically activates a swing arm on the transmitter $T$, which itself emits ultrasound waves that are picked up by receivers $R_1$ and $R_2$. Angle $\gamma$ indicates the orientation of the transmitter with respect to the magnetic field.

Fig. 4. Ultrasound transmitter, consisting of a bottom gold layer with a centered nickel insert, a plastic spacer, as well as a golden top layer with a suspended nickel body in the center.
Our acoustic transducer is manufactured using standard microfabrication procedures and is explained on the basis of the top swing element, which consists of a golden frame and a centered nickel insert. The fabrication steps follow the illustrations in Fig. 5.

Initially, wafers are cleaned using a 3:1 solution of $\text{H}_2\text{SO}_4$ and a 30% $\text{H}_2\text{O}_2$ solution in order to remove native oxides as well as organic and ionic substances from the surface. Additional treatment involving distilled water, as well as special drying, is required for the subsequent deposition processes. Electron-beam evaporation is then used to apply a good-adhesion titanium layer (25 nm), followed by a sacrificial copper layer (500 nm), and again, a final titanium layer (25 nm), as shown in Fig. 5(a). It follows the application of negative photoresist and its exposition to UV light through a quartz mask [Fig. 5(b)]. Subsequent development dissolves unexposed areas, thus revealing the top titanium layer which is later removed using a solution of 0.5% HF and 5.5% NH$_4$F. Further rinsing with a 10% solution of H$_2$SO$_4$ etches the negative oxides on the copper surface before the main gold structure is electrodeposited and the photoresist is removed [Fig. 5(c)].

The same procedure of applying and patterning photoresist, as well as pre-electroplating surface treatment, is repeated again, as shown in Fig. 5(d). It follows the electroplating of nickel parts and removal of the photoresist [Fig. 5(e)].

Finally, selective etching of the copper layer using a 3.5% solution of NH$_4$S$_2$O$_8$ and 7.28% NH$_3$ releases the parts shown in Fig. 6 from the wafer [Fig. 5(f)].

### IV. MICROASSEMBLY STATION

The assembly of the microfabricated components of the transmitters is performed using an advanced microassembly station. It is a serial system [11] with full 6 DOF and numerous advanced features for high-precision microassembly. A photorealistic render of the final product is shown in Fig. 7. The subsequent sections describe the individual components in more detail, starting off with the mechanical and kinematic configuration, followed by the vision and illumination setup.

#### A. Mechanical Setup and Kinematic Configuration

The core component of the system is a 6-DOF manipulator built from a 4-DOF base unit and a 2-DOF gripper unit, as shown in Fig. 8.

The strong dependence on visual feedback at the microscale requires that the view volume of the microscopes coincides with both the tip of the tool and the tool’s center of motion (TCM) [12]. Since the TCM is defined by the configuration of the rotational axes and preferred to be stationary, all rotational axes have to intersect in one point, also referred to as the remote center of motion (RCM). Fig. 9 shows this kinematic configuration which is also used in the system developed by [13]. The kinematic configuration in standard notation is shown in Fig. 9.
The 4-DOF base unit consists of a large backlash-free high-precision rotation table providing rotation $\theta$ around the $z$-axis. Its fairly large diameter is reasoned in the fact that the weighty $xyz$-stage is excentrically mounted on the output side on the top plate. In addition, the hollow construction with an inner diameter of 160 mm offers the integration of a rotary ring with a 2-channel pneumatic and a 36-channel electric feed-through, respectively. This design allows infinite rotation carrying pressurized air and vacuum, as well as drive and other control signals, respectively. The rotation table provides a theoretical mechanical resolution of $0.001^\circ$ and a typical eccentricity of 1.4 $\mu$m.

As previously mentioned, the round plate on the output side carries the $xyz$-stage as well as pneumatic and vacuum valves. It also contains a laser diode whose beam is coincident with the rotation axis used for calibration. Additional space allows mounting other components and, thus, offers flexibility for future developments.

The 2-DOF gripper unit provides the two remaining rotary degrees of movement $\eta$ and $\zeta$ around axes $x$ and $y$, respectively, and holds the end effector (microgripper). The unit consists of an arm that is arranged around the dome for design compactness. This arm is directly attached to a Harmonic Drive driven by an electric motor and a drive belt. The backlash-free and quiet operation of the Harmonic Drive, as well as the high gear ratio of 560 : 1, allow movements at high resolution. Similar to the base unit, the gearbox also has a hollow shaft that contains two concentric tubes which serve as a conduit for cables as well as the calibration laser beam. Electric wires as well as fibers for optical limit switches are all conducted inside special grooves of the curved arm. The last rotational degree of freedom $\zeta$ is again realized with a miniature Harmonic Drive combination that is attached to the very end of the arm unit. Two manual $xy$-stages mounted perpendicular to each other are used for alignment of the tool center point with the other rotation axes.

The end effector of the manipulator can be fitted with three different gripping devices depending on the type of application. Available are a mechanical, a MEMS, and a vacuum gripper.

The mechanical microgripper [14] consists of a pair of tiny comb drives in an array (actuation voltage: 0–150 V). The version used here has integrated force-feedback on the same device and can handle objects ranging from 5 to 200 $\mu$m with a maximum gripping force of 72 $\mu$N. This gripper has proven to be very versatile for a large variety of applications and is extremely robust.

A microfabricated MEMS gripper [15] has been developed and comes in different configurations. Their common actuation principle is based on electrostatic forces between numerous comb drives in an array (actuation voltage: 0–150 V). The version used here has integrated force-feedback on the same device and can handle objects ranging from 5 to 200 $\mu$m with a maximum gripping force of 70 nN. Dealing with objects that small is certainly the big advantage of MEMS grippers. However, their silicon body is very fragile and makes the device less robust.

As opposed to the tweezer-type mechanical microgrippers, their vacuum counterparts [16] hold parts by sucking them to a depression creating fixture. The primary advantage is the low complexity of those devices since they do not have any moving parts. However, the main issue is to control the orientation at which a part is aspirated and released. In addition, the contact surface on the part is not allowed to increase a certain roughness depending on the pressure of the vacuum.

Table I shows accuracy and precision values for this micro-manipulation unit.

### B. Vision and Illumination Setup

Vision sensory feedback is crucial for any microhandling station [17]. The microassembly station features a maximum of three individually adjustable ring units observing the manipulation scene. The units are attached to a metal ring whose central axis is collinear with the rotation axis $\theta$, and they can be configured with microscope cameras, glue dispensers, etc., depending on the type of application. The kinematic
configuration of each unit is shown in the little inset in Fig. 9. The working area is surrounded by a metal dome in the shape of a hemisphere providing customizable illumination conditions.

The main axes of the ring units are tilted down at a 45° angle from horizontal and equally spaced around the center. This configuration is beneficial for reducing the anisotropic sensitivity of microscope lenses that are unable to detect motion along the optical axis. It has been optimized by visualizing camera sensitivity through visual resolvability ellipsoids (refer to [18] for details). The present configuration uses two BASLER A602fc−2 color cameras on the first two, as well as a glue dispensing device on the third position.

A number of previous assembly experiments have shown that correct illumination is essential for micromanipulation tasks. Depending on the surface coating and the part shape, one has to adjust light sources so that disturbing reflections and shadows are reduced to a minimum. The present illumination setup consists of four individual systems combined in a compact centered vision dome (Fig. 10). The dome itself is not only a supporting structure and protection for the workspace but also creates diffuse ambient (indirect) illumination by the light of 12 high-power LEDs reflected at its inner matt-finished surface [see Fig. 10(a)]. Each of these emitters provides around 80 lm @ 1 A, yielding a total of 960 lm. Indirect lighting or dome illumination provides a diffuse and homogenous light without reflections, which becomes specifically useful when working with shiny spherical and convex objects.

The second illumination device is a single 1-W LED spotlight integrated in the summit of the dome [Fig. 10(a)] and focused on the RCM (Fig. 9). It offers a bright and concentrated pool of light on the workbench and works best with nonreflected parts or in other situations where strong illumination is needed.

A set of four equally spaced 1-W LED spotlight units arranged around the dome at a low angle of 14° are designed to emphasize even the smallest deviations on the surface [Fig. 10(b)]. This results in high-contrast images of the contours of any outstanding objects. As opposed to commercial low angle illumination systems, this implementation features two operation modes. In static mode, all four LEDs are triggered at the same frequency and zero phase shift. However, in rotation mode, they are triggered sequentially with the same frequency and a phase shift of one cycle. This effect of rotating light-sources around the center creates shadows on alternating sides and thus allows the creation of depth images that give a more realistic view of the scene.

In addition, six high-power UV LEDs are arranged at a 45° angle to the horizontal plane for curing UV glue during assembly sessions.

### TABLE I

**Accuracy and Precision of the Actuated Microassembly Axes**

<table>
<thead>
<tr>
<th>Axis</th>
<th>Label</th>
<th>Accuracy</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sutter</td>
<td>x, y, z</td>
<td>0.195 μm</td>
<td>± 0.025 μm</td>
</tr>
<tr>
<td>Axis 1</td>
<td>μ</td>
<td>0.016 μm</td>
<td>± 0.0016 μm</td>
</tr>
<tr>
<td>Axis 2</td>
<td>ζ</td>
<td>0.075 μm</td>
<td>± 0.025 μm</td>
</tr>
<tr>
<td>Newport</td>
<td>θ</td>
<td>0.01 μm</td>
<td>± 0.001 μm</td>
</tr>
<tr>
<td>Calib Y</td>
<td>cyz</td>
<td>165.806 μm</td>
<td>--</td>
</tr>
<tr>
<td>Camera n</td>
<td>jfn</td>
<td>0.1 μm</td>
<td>± 0.01 μm</td>
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All of the aforementioned light sources can be individually triggered, and their power regulated in the range of 0%–100%.

This novel advanced illumination system yields crystal clear images of the workbench area and offers the possibility to highlight certain areas. Fig. 11 shows four possible combinations of the individual light types, together with the corresponding histogram. While the spotlight highlights the center area from the top, the low angle illumination visualizes edges and even surface roughness. A combination of those two [see Fig. 11(c)] is a good choice for most applications. Diffuse or ambient illumination can be used for shadowless brightening of the scene.

Depending on the aperture setting of the microscope lenses the output power of the illumination is adjusted. With a 0.75× primary magnification and an aperture setting of roughly 20%, a configuration used for all experiments shown here, an output power of less than 75% was sufficient for all cases. The 25% reserve will be required once the apertures are fully closed or if parts are coated with a dark material. Since the driver electronics are designed to drive even higher power outputs, the present LED set can be easily exchanged with newer and brighter models.

#### C. VR Environment

Even though the mechanical configuration of the three optical microscopes provides at least one nonoccluded view of the assembly scene in good quality, problematic conditions, such as shadows and reflections, can impair the overall visual quality. Precise alignment of components is additionally impaired by the fact that the orthographic projection nature of high-magnification microscopes makes it impossible to capture depth information along their optical axes. Moving a second optical unit perpendicular to the first one can solve this problem and dramatically increase visual resolvability [18], but in most cases, this is practically impossible due to the tight space constraints. A more promising solution widely used in other areas is the mapping of the relevant mechanical hardware to a virtual environment in which viewports can be arbitrarily set depending on the current situation. The fact that 3-D model data of both the assembly hardware and the parts to be manipulated are readily available from the CAD driven design process, simplify the setup of the virtual world. The same data set can also be used for model-based computer vision tasks, such as initial pose estimation and tracking, and is thus stored in a common model database.

The system developed within the framework of the micromanipulation system is based on the open source scenegraph model OpenSG. This package provides excellent scene graph functionalities, integrates nicely with other libraries, and is widely used in a large community for a variety of applications. A custom-built visualization widget projects 3-D data to the screen and provides basic functionalities such as viewport orienting, zooming, showing/hiding of parts, etc. (see Fig. 12). The core of the system is the virtual reality (VR) control center which basically maps incoming motion commands from haptic input devices to real axes of the hardware. Apart from this joint mapping, joint limits as well as constraints can be configured.
Fig. 10. Multipurpose illumination dome made out of aluminum with spot-, ring-, ambient, and UV-lighting. Cross-sectional view from the side (a) and the top (b).

Fig. 11. Comparison of different illumination types. Ambient illumination (d) gives a narrow histogram representing the diffuse character of the light resulting in a shadowless scene. On the other hand, spot (a) and low angle illumination (b), as well as a combination of them (c), yield a histogram with two peaks that are beneficial for automatic image thresholding.

offline and thus offer unprecedented flexibility for controlling any type of machine, not only the microassembly station. The fact that every motion command is checked by a collision detection routine before it is actually sent to the real hardware decreases the chance of accidentally damaging gripper and/or parts. Last, the virtual representation of the real scene is not directly influenced by the haptic input devices, but reacts on encoder feedback from the hardware or position information from computer vision algorithms.

Safety routines, such as collision detection, as well as command transfer over a regular Ethernet network infrastructure introduce a lag from input command to visual feedback on the order of 0.5 s to the present system. This is acceptable and does not seem to impair the look and feel for most users.

V. ASSEMBLY OF ACOUSTIC TRANSMITTERS

Precise placement of the three individual components is crucial for a successful operation of the final device. Mis-alignment of the nickel bodies immediately results in greater magnetic losses and, thus, impairs overall performance. Despite the relatively large size of the elements, manual assembly has proven to be inefficient, tiring for the operator and not precise enough. On the other hand, the design and flexibility of the microassembly system can handle these types of objects.

Base element, spacer, and swing element are placed on the workbench and held in place by the vacuum underneath. Accurate placement with respect to position and orientation is not crucial since the manipulator is able to reach and location on the workbench. However, for reasons of simplicity, parts are placed equally oriented next to each other in all experiments.

Small droplets of UV-curable glue are deposited on two opposing sides of the base using a miniature pipette, as shown in Fig. 13(a). Next, the plastic spacer is picked at a ligament in a corner [Fig. 13(b)] and exactly placed and aligned on the base [Fig. 13(c)]. UV illumination can now be used to fixate these parts. However, adhesive forces are large enough to keep the spacer in place while proceeding with the assembly. This time, the upper part is gripped at one of its two spring elements first [Fig. 13(d)] and then the glue dispensing needle deployed. This sequence minimizes the time which the glue is exposed to air. Again, small droplets of UV glue are applied to two opposing corners [Fig. 13(e)], and the upper element is precisely placed on the existing structure. The gripper fingers are then used to compress the sandwich in order to squeeze out excessive amounts of glue, thus reaching design dimensions. Finally, intense UV illumination is used to cure the glue and to fixate the whole structure. Due to the fact that the UV rays do not reach the small inner spacings of the structure, the transducers are kept in a warm and dry place for 24 h after which they are fully operable.

This process has proven to be very efficient with a yield rate of more than 80%. Optical inspection under a regular microscope has shown an average lateral alignment within the order of 1%.

The present microassembly system can also be used for a first function check of the assembled devices. For this purpose, the gripper is used to push down the swinging mass. The visual analysis of the upper and lower swing yields a maximum range of movement on the order of ~200 μm, which agrees with the design parameters.
VI. EXPERIMENTAL RESULTS

A coil with 18-mm radius and 21 turns is used to generate the magnetic field. The coil is driven by a custom-built current amplifier that controls the input current to the coil. The amplifier input signal is an on/off signal with frequency \( f \) and varying amplitude proportional to the desired current, and is generated on a data acquisition card (NI-6110) in a PC.

Fig. 14 shows the first three modes of the resonator as measured by a laser Doppler vibrometer (LDV) in air and simulated with a FEM modal analysis using ANSYS. Good agreement is found between the experimental and FEM modal analysis. For the amplifier input signal \( f \), the measured frequency \( f_{\text{LDV}}^1 \) is used, such that the acoustic transmitter is excited at its first resonance.

Fig. 15 shows a sketch of the experimental setup. The transmitter is glued to the wall of a container that is filled with water or glycerine. The driving coil is placed below the container (A, corresponding to \( \gamma = 0^\circ \) in Fig. 3) or at the wall of the container (B, corresponding to \( \gamma = 90^\circ \) in Fig. 3), such that the transmitter lies on the axis of the coil. The magnetic

![Fig. 12. VR visualization widget with four configurable viewports.](image1)

![Fig. 13. Assembly of an ultrasonic transmitter. Two droplets of UV-activated glue are deposited on opposing sides of the bottom gold layer (a). The plastic spacer is gripped (b) and precisely aligned with the base (c). The same procedure is reproduced again for the top swing element (d) and (e). Finally, the structure is compressed by pushing the gripper on the upper central nickel body (f) so that the glue can be hardened.](image2)

![Fig. 14. Modal analysis: Good agreement is found between the experimental data \( f_{\text{LDV}}^1 \) (LDV) and numerical analysis \( f_{\text{FEM}}^1 \) (ANSYS). (a) \( f_{\text{LDV}}^1 = 4.13 \) kHz. (b) \( f_{\text{FEM}}^1 = 4.14 \) kHz. (c) \( f_{\text{LDV}}^1 = 5.76 \) kHz. (d) \( f_{\text{FEM}}^1 = 5.28 \) kHz. (e) \( f_{\text{LDV}}^1 = 13.44 \) kHz. (f) \( f_{\text{FEM}}^1 = 12.53 \) kHz.](image3)
output signal from the coil excites the resonator close to its first measured resonance mode at $f = f_1^{LDV}$. The pressure wave generated by the transmitter relative to the ambient pressure is picked up by a receiver placed at 1 cm from the transmitter. The receiver is a cubic piezostack with 2-mm side length made from lead zirconium titanate and sealed with silicone rubber. The pressure change recorded at the receiver is bandpass filtered, amplified, and transferred back to the data acquisition card.

Water is selected as a fluid because it has acoustic properties similar to human tissue, e.g., the speed of sound in water and fat is very similar. To represent tissue like muscles with higher speed of sound glycerine is used.

For the two coil positions and the two fluids, we perform a fast Fourier transform (FFT) on the recorded acoustic signal for different applied currents. Fig. 16 shows a typical result compared to the frequency response recorded by the LDV where the coil was driven with periodic frequency chirps. The peaks occurred in the measured frequency response from the LDV correspond to the first four modes of the transmitter. Due to the excitation of the transmitter with its first natural frequency, the FFT of the acoustic signal shows only very sharp peaks at the first mode and the corresponding harmonics (integer multiple of the fundamental frequency).

Fig. 17 shows the experimental results for water and glycerin as well as the two coil positions (A and B in Fig. 15). The results are normalized to the pressure level at an applied current of 4 A. It can be seen that the experimental pressure results are quadratic in the applied current.

As the transmitter works at resonance, the direction of the excitation field can be arbitrary as shown with the two experimental arrangements with $\gamma = 0^\circ$ and $\gamma = 90^\circ$. Nevertheless, the transmitter sends out an acoustic signal at the desired frequency. This is an important feature for devices operating inside the human body, where accurate position and orientation control is difficult. With the proposed transmitter, localization independent of the pose of the device is possible. In addition, its wireless nature reduces considerably the power requirement of the devices while their functionality is increased.

**VII. Conclusion**

The development of advanced medical devices for minimally invasive surgery is strongly dependent on wireless data transmission and localization techniques. While the first topic offers many practicable solutions already widely used, solutions for accurate pose retrieval inside the human body are less established. Our competence in the fields of ultrasound and magnetic actuation lead to the development of ultrasonic transducer modules, which are of relatively low complexity and yield excellent performance in localization accuracy. The assembly of those devices is very suited for a recently developed microassembly system, capable of manipulating MEMS components with micrometer precision in full 6 DOF. This case has shown that the manipulator is also capable of handling larger and heavier objects even though the design is optimized for submillimeter components. It has also proven the flexibility of the system allowing not only the actual manipulation but also functional checks, as well as the mechanical characterization of final assemblies. Advances in mechanical design, illumination, as well as user interface design make state-of-the-art micromanipulation systems important tools in many research and industrial environments.
REFERENCES


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Dr. Nelson has been awarded a McKnight Land-Grant Professorship and is a recipient of the Office of Naval Research Young Investigator Award, the National Science Foundation Faculty Early Career Development Award, the McKnight Presidential Fellows Award, and the Bronze Tablet. He was elected as an IEEE Robotics and Automation Society Distinguished Lecturer in 2003 and 2008, and has been a finalist for and/or won best paper awards at major robotics conferences and from journals in 2004, 2005, 2006, 2007, 2008, and 2009. He was named to the 2005 “Scientific American 50,” Scientific American magazine’s annual list recognizing outstanding acts of leadership in science and technology from the past year for his work in nanotube manufacturing. He serves on or has been a member of the Editorial Boards of the IEEE TRANSACTIONS ON ROBOTICS, the IEEE TRANSACTIONS ON NANOTECHNOLOGY, the Journal of Micromechatronics, the Journal of Optomechatronics, the Journal of Biomechatronics and Biomedical Robotics, the Journal of Micro-Nano Mechatronics, and the IEEE Robotics and Automation Magazine.