Sandia National Laboratories

University Alliance

Novel Design Competition

April 6, 2007

University of Oklahoma

School of Aerospace and Mechanical Engineering

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Executive Summary

The University of Oklahoma submits *Parvissimus Bracchius* (Latin translation, "smallest arm") to the Sandia National Laboratories' University Alliance Novel Design Competition. *Parvissimus Bracchius* has three major components that are unique, novel, and innovative. First, using on-chip actuation, this design *automatically* rotates a structure with sizable length (e.g., mm) to a vertical position that is orthogonal to the plane of the chip. Second, *Parvissimus Bracchius* is designed to provide electrical power (insulated hot and ground leads) to the top of the vertical structure once it is upright. Third, at the top of the vertical structure which rises significantly above the substrate, it provides real estate space for micro-tools that move and perform work. The micro-tool has a telescopic accordion-like arm with the ability to reach up and grab something over 300 μm above the top of the *elevated* structure which is about 1.5 mm above the substrate of the chip. In summary, *Parvissimus Bracchius* is the realization of three novel design features: automatic 90 degrees rotation of released MEMS structures into vertical orientations, electrical power supplied up through the elevated structure, and micro-tool work and movement at the top of the elevated structure. These three realizations are steps toward opening up some additional exciting potential applications in various fields including nanotechnology, biomedical, micro-manufacturing, micro-fluidics, and micro-sensors.

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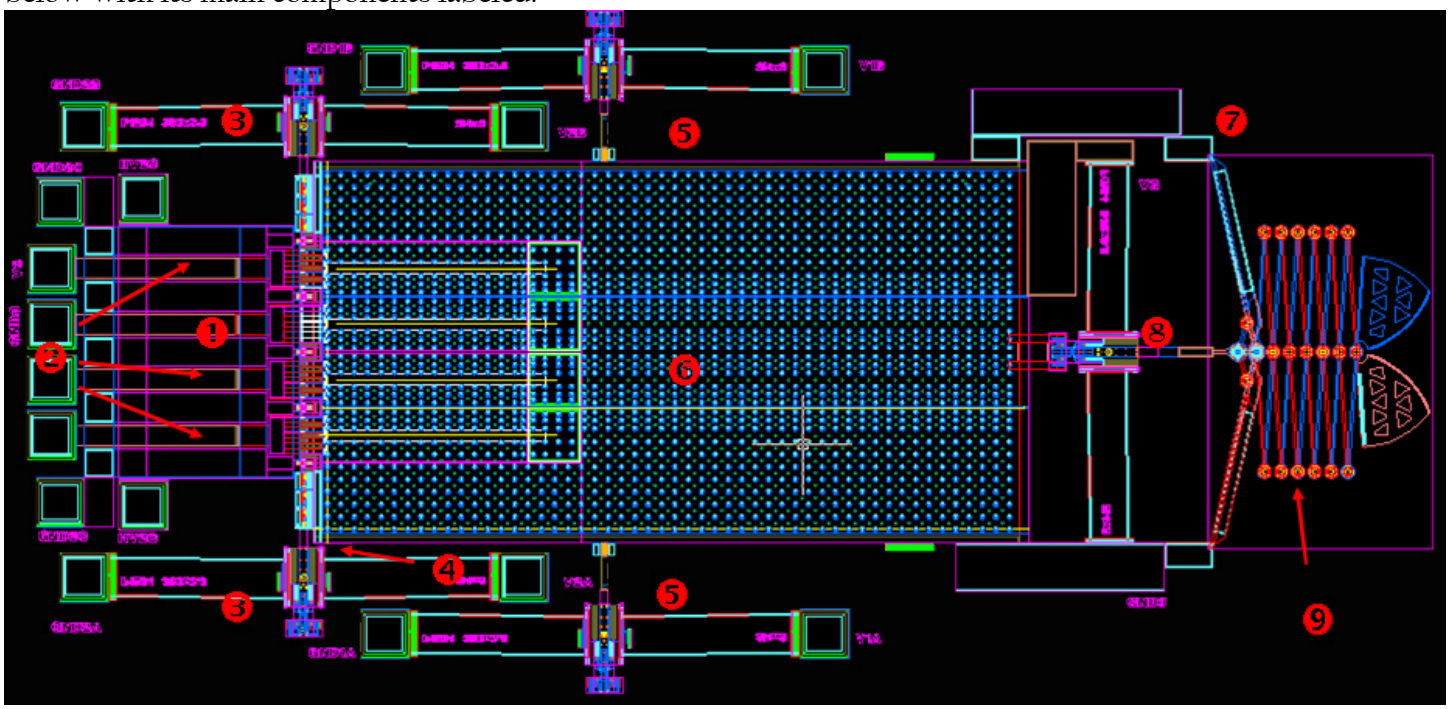
Section 1: The Idea

The concept for the device is to give a MEMS chip the ability to interact in three dimensions. *Parvissimus Bracchius* contains an arm that raises into a position orthogonal to the chip, allowing one of several different tools to come into contact with the space above the chip. The different tools allow *Parvissimus Bracchius* to become one of any number of different mechanical devices: a measuring tool, a cutter, a grabber, a manipulator, or a specialized tool designed to complete a specific task.

The geometry of MEMS devices creates a product that is, in effect, a two and half dimensional object. Therefore, having the ability to raise part of the device and interact in the third dimension will give MEMS devices new and progressive 3-D abilities. There are numerous potential applications, including interaction with a second chip in a flip-chip system or allowing the raised chip to interact on a new level within its working environment. While structures can be raised up manually (e.g., probe tip actuation), *Parvissimus Bracchius*, using on-chip actuation, will erect itself into a vertical orientation using its own means. In addition, electrical power will run up the vertical structure in order to run the micro-tools at the end of the operating plane. These two features make *Parvissimus Bracchius* a unique and innovative endeavor in the world of MEMS. As far as preliminary research has indicated, there are no such MEMS devices that provide either the capability of erecting itself to an upright position or the ability to supply power to a micro-tool on top once it is in an upright position.

Section 2: *Parvissimus Bracchius*

The critical components to this device operation are explained in this section. A picture of the device is located below with its main components labeled.



1. **Ground Lead:** it provides ground for the micro-tool on the top of the operating plane (6).

2. **Hot Leads:** Three hot leads are designed into our device. One hot lead is needed for each micro-tool powered at the top that is required to do a function (i.e., extend the arm, close the grabber, etc.). These leads connect into the "oxide encased" interior core structure of the operating plane (6).

3. **Thermal Actuators with Jacking System:** These incrementally jack the operating plane (6) from its horizontal position to a 90 degree vertical orientation.

4. **Pin and Cross System:** These use a set of angled crossbars set at 15 degrees to the shaft that when drawn forward, apply a torque on a set of pins orthogonally attached to the shaft at the base of the operating plane. The torque on the shaft rotates the operating plane 90 degrees into a vertical orientation. There are three such systems on each side of the shaft so that the maximum pointwise torque locally on the shaft is reduced by a factor of three.

5. **Thermal Actuators and Latch:** These latches keep the operating plane secure while it is not being elevated.

6. **Operating Plane:** The operating plane is the main body that is being elevated 90 degrees. The blue circles are the pores in the operating plane. These allow etching through to the substrate layer which will release the operating plane from the surface of the chip. The operating plane contains an exterior grounded case-like structure and an interior core-like structure encased in oxide that allows it to be insulated from the ground of the case and that allows it to serve as the hot lead for the tool (9).

7. **Tool Connection:** These anchor the tool struts to the operating plane to provide rigidity. These also anchor the thermal actuator where it connects to the operating plane ground.

8. **Thermal Actuator for Tool:** The thermal actuator located on top of the operating plane is used to supply force for the micro-tool to do work. It contains a jacking system that permits the micro-tool to reach its full telescopic extension.

9. **Micro-Tool:** The Telescopic Extension Arm gripper tool is equipped with two-way and three-way bearings so that 3 different structures can rotate separately from each other at the same "joint". It is equipped with a twin set of micro-shark-jaws for gripping its prey.

Bond Pads

Bond Pad	Application
1A*	When 4-6 V are run through these bond pads, this will displace the thermal actuator and activate the jacking system, disengaging the latch holding down the operating plane during release.
1B	Same as 1A
2A	When 4-6 V are passed through these bond pads, the displacement of thermal actuator will activate the jacking system, drawing a twin set of crossbars past a pin which is attached perpendicular to the shaft of the operating plane. This will put a torque on the shaft and thus cause the entire operating plane to rotate into a vertical orientation.
2B	Same as 2A
2C	These bond pads will require a pull-down voltage of approximately 35 V o to pull down the spring-like contacts of the hot and ground leads that are underneath the shaft of the operating plane. These need to be pulled down to allow the operating plane to rotate freely into its vertical orientation. Once the plane is fully rotated 90 degrees, the pull-down voltage to these bond pads is then turned off, allowing the spring-like contacts to make physical contact with the shaft and base of the operating plane. This will allow electrical power to be supplied to the top of the plane.
3	These will require 4-6 V, and they will supply power to the micro-tool at the top of the operating plane. This voltage should only be applied when the operating plane is in its final vertical orientation. Applying a voltage to Bond Pad 3 will cause the telescopic arm of the micro-tool to extend and the tool's micro-shark-jaws to grab its prey.

*Refers to Hot V1A and Ground GND1A. This nomenclature is consistent for all other bond pads as well.

Thermally Actuated Jack Lift System

The operating plane of our design is to be raised 90 degrees by a thermally actuated jacking system. The jack itself is simply a thermal actuator with a ratcheting centerpiece designed to incrementally drive a series of cross-shaped transmissions that convert rectilinear motion into a rotation motion. The thermal actuator is capable of producing at least 10μm of rectilinear travel relative to 4μm-spaced ratchet teeth that are fixed to the substrate. This means that each actuation pushes the cross-shaped transmission device the length of two teeth, or 8μm. The cross-shaped transmission components are designed to convert the force provided by the thermal actuators into a torque on operating plane's shaft to erect it. Pins that are fixed perpendicularly to the shaft are rotated by the cross-shaped transmission components which are aligned 15 degrees with respect to the shaft. The torque induced on the shaft incrementally raises the operating plane to a position orthogonal to the substrate. As the cross-shaped transmission components travel a distance of 18μm, the operating plane and its shaft are rotated 90 degrees into a vertical orientation. Three cross-shaped transmission components are located on each end of the shaft to lower the maximum pointwise torque by a factor of three and thereby reduce the maximum shear strain on the shaft during the 90 degrees rotation of the operating plane.

Operating Plane Latch System

During the release phase of the SUMMiT V™ fabrication process, there are tremendous forces that can potentially damage a design if the device is not securely anchored to the chip. To minimize that risk, a thermally actuated latch is located on each side of the operating plane to secure and safeguard it until it is time to raise it into its vertical operating position. At that time, the latches are released by activating the "side" thermal actuators, freeing the operating plane from the substrate plane.

Operating Plane and Its Electrical Leads

The operating plane in its vertical position provides electrical power and vertical offset for micro-tools functions on top. Our particular operating plane rises about 1.5mm above the substrate and is about 800 microns wide to accommodate real estate space for micro-tools. Its base is attached to the shaft that is rotated by the thermally actuated jack lift system as described above. Our particular operating plane is composed of 3 separate circuits for powering up micro-tools on top. A sufficient number of release holes/pores are provided so that the operating plane is released from the substrate. The operating plane is ribbon-cable like in its structural composition. It is made up of "inner" and "outer" polysilicon layers in which an interior one is encapsulated in an oxide to insulate it from the exterior layers that serve as ground. These polysilicon layers serve as electrical leads for bringing power source to the top. The interior/core polysilicon layer which serves as the "hot" lead for power at the top runs the full length of the operating plane and makes physical contact with spring-like contacts on the substrate which in turn are connected to "hot" electrodes on the chip. In effect, electrical 'wires' have been created that enable voltage/current to be carried to the micro-tools mounted at the top of the operating plane. The exterior/shell polysilicon layers of the operating plane make physical contact with spring-like contacts on the substrate which in turn are connected to a "ground" electrode on the chip. The spring-like contacts on the substrate are pulled down and out of the way using electrostatic "pull-down" voltages before the raising of the operating plane into its vertical position. When the spring-like contacts are "let" go after the operating plane has attained its vertical position, they press hard against the hot and ground leads of the operating plane for continuity of circuit.

Telescopic extension gripper

The "shark-jaws" gripper as micro-tool is located at the top of the operating plane and demonstrates the ability to extend a micro-tool beyond the top. For the purpose of illustrating powered motion at the top, two gripping jaws, called "shark jaws", are attached to the end of a telescopic extension system, allowing the device to grasp three-dimensional objects as it extends out into 3-D space. The gripper is powered by a single thermal actuator. The extension distance of the gripper is a function of the thermal actuator's displacement. A maximum thermal actuator displacement of 15μm results in a reach distance greater than 300μm.

Section 4: SUMMiT V™

This device would not be possible in a typical four layer system. Since P1 and P2 are nearly always bound together to make a layer of comparable thickness to P3, the rotating system, the power at the top of the operating plane, and the telescoping extension gripper would all be infeasible without the P4 layer as they need all of the five layers to operate correctly. *Parvissimus Bracchius*' unique ability relies on being able to use the constructional richness of the P1, P2, P3 and P4 layers. The gripper system uses P1, P2, and P4 to make two separate bars with hinge pins that are comprised of P1, P2, P3 and P4, allowing the bars to rotate and the scissor-jack to expand and contract. The "pin_joint" layer was crucial in designing the two-way and three-way bearing. The P1 layer together with the Sacox2_cut layer was crucial in designing the spring-like contacts for bringing power onto the operating platform. Without the full technology and processes of SUMMiT V™, *Parvissimus Bracchius* would remain merely an interesting idea instead of a fully developed design.

Section 5: Educational Demonstrations

Many current MEMS devices can be difficult to comprehend, especially as many use very subtle mechanisms and work on a scale that is less intuitive than macro-scale applications. This makes demonstration to less technically-experienced people a difficult task. However, even very young children can easily understand the usefulness of an arm. Consequently, a device such as *Parvissimus Bracchius* will be especially useful for educational demonstrations geared towards the younger members of the K-12 age range, and others who may have trouble understanding MEMS devices. An arm that reaches out and essentially has tiny "power tools" on the end is much easier to explain than inkjet printer heads using the piezoelectric effect, even though the printer is a device more common to them. A device like *Parvissimus Bracchius* will open a simple and understandable application in a complex field. *Parvissimus Bracchius's* more technical aspects will of course be more appropriate for the older members of the K-12 age range as well as the post-secondary students. While MEMS is a highly technical field, the mechanics of the jacking system and telescopic extension gripper can be understood by higher level students and can excite interest in MEMS technology.