Prefatory Material

a. Organization: Department of Aeronautics and Astronautics
   Stanford University
   Stanford, California 94305

b. Title: Mesicopter: A Meso-Scale Flight Vehicle for Atmospheric Sensing

c. Type of Organization: Educational Institution

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e. No other organizations are currently evaluating a proposal for the same effort.

f. Call for Proposal: CP 98-01 Advanced Concepts Program, Phase I.

g. Dollar amount requested: $70,000
   Desired starting date: 10/1/98
   Duration of project: 6 months

h. Date of submission: 7/31/98
Technical Proposal: Mesicopter—A Meso-Scale Flight Vehicle for Atmospheric Sensing

Abstract
A team of researchers from Stanford University, SRI, and M-DOT corporation propose to build the ‘mesicopter’, a centimeter-size electric helicopter designed to stay airborne while carrying its own power supply. This device represents a revolutionary class of flight vehicles at an unprecedented size and suggests a range of potential uses. The proposed work focuses on the development of mesicopters for atmospheric science, permitting in-situ measurements of meteorological phenomena such as downbursts and wind sheer, and with unique capabilities for planetary atmosphere studies. Swarms of mesicopters could provide atmospheric scientists with information not obtainable using current techniques and could aid in the understanding of phenomena that play a critical role in aviation safety. Better characterization of atmospheric phenomena on Mars and other simple sensing tasks may be feasible, with these very low mass and low cost aerial micro-robots. The mesicopter will pioneer the application of new aerodynamic design concepts and novel fabrication techniques including solid freeform fabrication and VLSI processing steps. These techniques may ultimately allow the mesicopter to be scaled down to millimeter dimensions. Significant challenges are anticipated in the areas of materials, battery technology, aerodynamics, control, and testing. This proposal describes work for the first phase of the program in which initial designs and fabrication tests are used to evaluate the concept’s feasibility. An outline of subsequent phases is also provided.

Advanced Concept Description
The possibility of constructing swarms of tiny flying devices is intriguing. Conceivable applications range from a variety of in-situ measuring tasks to synthetic communications relays, from military surveillance to planetary ‘probe-droids’. To pursue any of these applications a number of fundamental questions need to be answered first: “Can we effectively shrink large flying machines to micro dimensions?”; “Which performance parameters improve with decreasing scale?”; “Which ones degrade?” To answer some of these questions, a team of researchers from the Aeronautics and Astronautics Department, the Mechanical Engineering Department and the Stanford Nanofabrication Facility at Stanford University, as well as SRI and M-DOT Corporation proposes to build the “Mesicopter:” a centimeter size electric helicopter designed to stay airborne while carrying its own power supply.

The Aero-Astro Department has a long history of designing, manufacturing, and testing innovative flying devices. The Rapid Prototyping Laboratory (RPL) and the Stanford Nano-fabrication Facility (SNF) are hosting state-of-the-art manufacturing facilities for building integrated silicon/metal/ceramic devices as required for the realization of the Mesicopter. SRI is a leader in advanced battery development. M-DOT is an entrepreneurial company with strategic interests in bringing innovative flying devices to the market. In the first phase of this proposed study, Stanford researchers will try to answer questions of feasibility and fabrication approach in preparation for subsequent phases in which the entire team will propose to build and fly such a device. The first phase will address system issues ranging from aerodynamic performance to rotor and mesomotor control, airframe dimensions and material, integration of battery power supply, sensor and communication facilities, as well as fabrication and assembly methodologies.

The Mesicopter will be built of a combination of novel SFF (Solid-free-form Fabrication) techniques and established VLSI processing steps. These techniques may ultimately allow the Mesicopter to be further scaled down to millimeter dimensions. Significant challenges are anticipated in a number of areas including material selection, mechanical tolerances, battery power and energy, motion control, and testing. Experiments with the proposed mesicopter platforms will address open issues regarding aerodynamic performance of centimeter and sub centimeter scale devices, a largely unexplored field. The validity of scaling law predictions regarding power, lift, and size will be established. Theoretical and experimental research in the centimeter size regime area is considered crucial for speculating about the aerodynamic performance of even smaller devices.

While the focus of this proposal is on the design, fabrication, and testing of an individual helicopter, the implications of large numbers of mesicopters operating in concert will be a natural extension and application of the proposed research. One of the numerous advantages of producing machines in the mesoscopic size range is that many such machines can be mass produced using lithographic or other parallel processing techniques. As a result, comparatively simple devices can be made inexpensively in
large quantities. Groups of inexpensive, redundant mesoscopic devices could work together to achieve results greater than those from a single, large device. Swarms of tiny helicopters could perform a variety of functions that would have not been previously possible. Our work will focus on the development of the vehicle itself, and not a payload system, so we envision direct applications of these devices for measuring atmospheric disturbances such as wind shear, micro-bursts, and atmospheric turbulence—phenomena that are of critical importance to aviation safety. With simple transponders and triangulating receivers, a swarm of these devices could provide an instantaneous picture of air motion, leading to an improved understanding of such events.

Our team proposes to develop two prototypes of meso-scale helicopters or “mesicopters,” one with a size of about 3 centimeters and the other approximately 1 centimeter in diameter. The proposed devices will be driven by an array of 4 to 6 electric motors, each with outside dimensions ranging from 3 down to 1 millimeter and power of approximately 100 to 10 milliwatts. Early mesicopter design will be limited in control, but will be able to carry its own batteries. Later versions could be equipped with sufficient sensors and on-board control logic to maintain predefined positions in space.

Figure 1. Conceptual view of the Mesicopter
Figure 2. Plan view and side views.

Scaling Considerations
One cannot produce a flight vehicle in this size class by starting with an efficient large-scale configuration and scaling it down. Square-cube law considerations provide significant advantages in strength, stiffness, and heat transfer capabilities, while the fluid dynamics for such low Reynolds number flight and the fabrication approach constitute major challenges.

Impact of scaling down flying devices: Flying devices require power to overcome losses from two sources: the inviscid drag due to the lift of finite-span wing and the skin friction or viscous drag. At smaller scales, the effects of viscosity become increasingly important and the ratio of wing lift to drag (L/D) is reduced. Because the thrust required by the propeller for fixed wing aircraft is related to the weight by: \( T = W / (L/D) \), (see Figure 3) the required thrust approaches the vehicle weight as L/D approaches 1. However, the required power varies with the product of speed and thrust, so the point at which it is best to balance weight directly with thrust occurs at L/D values substantially higher than 1.

Figure 3. Fixed wing performance advantages diminish with size as L/D is reduced. Figure 4. Advantage of helicopters over fixed wing at Low L/D
The plot in figure 4 illustrates how the power required for hover compares with that required for fixed wing airplane in forward flight. Although the helicopter must generate more thrust than the propeller of the airplane whenever \( L/D > 1 \), the increased forward speed of the airplane makes the required propeller power greater than that of the helicopter even when the airplane \( L/D \) is as high as 3-6. The results are functions of aspect ratio (AR) and lift coefficient (\( C_L \)), a measure of the amount of lift that is generated per unit area at a given speed. At larger scales \( C_L \) of order 1.0 are achievable, while very small air vehicles would be restricted to \( C_L \) of about 0.5. Low power-to-weight ratios, required for flight at these small scales, is achieved by reducing wing loading and flying at very low speeds as \( P/W = V/(\sqrt{L/D}) \), where \( V \) is propeller efficiency. This approach leads to difficulties with control in the presence of even small-scale turbulence. Helicopters maintain high tip speeds without forward speed and are able to maintain flight in conditions that would be unacceptable for low speed fixed wing aircraft. So, in addition to their capability for maintaining position by hovering, helicopters compare favorably with fixed wing aircraft in efficiency at these scales.

Meso-scale rotor aerodynamics: Although simple scaling considerations suggest that the disk loading, and hence required power-to-weight ratio, may be reduced as the dimensions of a rotary-wing aircraft are reduced, many fundamental difficulties appear as this is extended to the scales contemplated here. The principal difficulty is associated with the very low Reynolds numbers and viscous-dominated flow regime that requires unconventional approaches to rotor design. Two problems arise in this domain: the first involves the increasing importance of viscous drag as dimensions are reduced, lowering the rotor efficiency and requiring substantially more power than larger rotors of similar loading. The large profile losses must be included in the design of the rotor planform to avoid very inefficient operation. These large section drag loads result in a reduced optimal rotation rate that exacerbates the second problem with very low Reynolds number rotor design: that of generating sufficient section lift. At the scales considered here, sections must be designed to maintain attached flow even with fully laminar boundary layers. The reduced mixing makes it difficult to avoid laminar separation at the lift coefficients desired for efficient rotor performance. A family of high lift, ultra-low Reynolds number sections has recently been designed by Stanford researchers and will be developed further in the proposed program.

Scaling of motors and airframe: The required power-to-weight ratio depends directly on the disk loading (weight / rotor disk area) and the viscous drag coefficient. Although the achievable disk loading may be reduced at small scales because of improved strength and stiffness properties, the viscous drag coefficients increase as the scale (and Reynolds number) is reduced. This leads to a requirement for even lower disk loadings than would be required for a larger vehicle. However, the power density that can be delivered at small scales may be increased. For example, very small electric motors may be able to deliver higher power densities than their larger cousins because small motors can better dissipate waste heat due to their larger surface area to volume ratios. Current research indicates that tiny gas turbine engines can deliver much higher power densities at small scales due to increased operating speeds. The chemical fuels used in tiny gas turbine engines give them an additional advantage over battery powered motors in terms of energy density. Despite the apparent theoretical advantage of turbine engines, however, we will focus our feasibility study on the use electric motors in this proposal for a number of practical reasons. Finally, it is also easier to use light, high-strength materials like silicon or ceramics in small devices. Unlike more ductile materials such as metals, the mechanical reliability is governed by the size of flaws within the part. Assuming a homogenous flaw distribution per volume, a smaller part is less likely to have a flaw exceeding the critical dimension and thus is less likely to fail than a larger part. This allows the use of very light, strong materials which reduces the mass of the hovering device and thus the required power density.

Advances in the state-of-the-art

The mesicopter is a bold concept requiring several advances in the state-of-the-art, not only in pushing the lower limits of flight, but also in the manufacturing processes needed to create this small system. The following identifies the specific advances that are needed for this small air vehicle. The method of accomplishing each is detailed in the Research Plan.

The mesomotor: While a great deal of work has been accomplished at the micro scale, especially for electrostatic motors, little work has been done on induction motors at the meso scale. In addition to the novel manufacturing processes used to build a motor at these geometries, several additional problems must be solved. To eliminate friction, the movable rotor shall be suspended dynamically by controlling
the magnetic fields that provide the rotating forces in the motor. The propeller and shaft produce a force that is perpendicular to these fields and friction due to this force must also be overcome. Solid state motor control is integrated into the support structure and provides the sequencing of current to the armature coils to not only control speed, but also to suspend the rotor. Finally, while we seek a long term goal of self-assembling processes, the focus of the motor development is to demonstrate feasibility and several manual assembly steps shall be required.

The rotor: Most of the work on propeller and rotor design that includes viscous drag treats it as an afterthought, extending inviscid design ideas to include performance penalties associated with skin friction. The present application requires that low section L/D and limited lift coefficients be included directly in the design philosophy. This will be accomplished with a combination of analytical work and nonlinear numerical optimization. A simple theory for viscous propeller design is in development and will be augmented by high fidelity computational aerodynamic analysis. The design of airfoil sections for the rotor will also constitute an advance in the state-of-the-art. The all-laminar section design will start from seed sections defined by simple theory. These sections will be refined using CFD design techniques that are well validated, yet not previously used in this domain.

The power supply: The battery technology is based on advanced lithium-metal technology and is to be manufactured in a monolithic process utilizing the same silicon substrate that serves as the airframe and also incorporates the electronics. The manufacturing process for the battery is novel in that we propose to build a layered structure on the backside of the silicon airframe. The important challenge here is to maximize use of the small amount of area, utilizing multiple layers of battery structure if possible.

System assembly: The elements of the unassembled mesicopter are not only small, but also quite fragile. Therefore, assembly is a significant challenge. In order to reduce cost and minimize yield loss during manufacture, self-assembly techniques shall be used wherever possible. The airframe, for example, is totally monolithic and the proposed process for batch manufacture of this component is quite similar to integrated circuit manufacture. Motor component manufacture and assembly is also a parallel batch process which facilitates gang assembly of the components of the motors and rotors. Gang assembly is also planned for mounting of the motors on the airframe.

Advanced Concept Development Plan

For each key element of the mesicopter, the following sections describe the research plan, the materials to be used, the fabrication process, tests that are planned for that element, and how risk will be mitigated. Then, the assembly plan and the plan for overall system performance evaluation completes the research plan. In parallel with the individual research tasks, two versions of the mesicopter shall be used as integration platforms. The first, using commercially available motors of 3 mm diameter shall be used to perform early investigation of flight dynamics and control for air vehicles of this size. The second, smaller device shall be used to investigate design and manufacturing issues related to the motors, battery and integrated airframe structure. Specific performance demonstrations of both these devices shall be used to permit independent development of the corresponding technologies.

The mesomotor

Since the manufacturing process developed at Stanford imposes few restrictions on the motor design, the design of the motor is mainly dictated by the requirements for the mesicopter. The power requirements from the mesicopter determine the size of the mesomotor, whereas the arrangement of the components is chosen to minimize the number and complexity of parts to connect the motor to the main frame and to the propeller while maintaining its high performance.

Design of the mesomotor: There are a variety of electric motor designs, following different physical principles and offering different levels of performance. The main advantage of an electrostatic motor design, for example, is its simplicity and the relatively low electric losses in the materials. Functional motors of this type with a few tens of microns diameter have been built out of silicon.\textsuperscript{1,2} However, the

\textsuperscript{1} Suzuki, Kenichiro, "Single crystal silicon rotational micromotors", Proceedings of the 1991 IEEE Micro Electro Mechanical Systems
forces from the electrostatic field are fairly weak (the energy density of the magnetic field is orders of magnitude higher, the same applies to forces). Because of the greater power density, magnetic field based motors are very attractive, despite the difficulty of fabricating the armature coils on a very small scale. Since very small gear boxes are difficult to make, the comparatively high torque at reasonable rpm makes magnetic field based motors much more suitable for technical applications.

With constant magnetic or electric fields, the power density of both the electrostatic and the magnetic motor scales favorably as the design gets smaller. The power density of electrostatic motors is limited by friction. The low energy density of electric fields in electrostatic motors requires them to spin at substantially higher rpm than a magnetic motor similar in size. In contrast, the power density of magnetic motors in the sub-millimeter range and below is mainly limited by electric losses in the armature coils. As the design gets smaller the motor has to operate at reduced magnetic fields, which means lower power density.

Because we have a manufacturing system in place that can produce accurate parts from a wide variety of materials, including hard and soft magnetic alloys, we have selected a permanent magnet excited brushless DC motor, which promises to offer the highest performance and best suitability for the mesicopter. Brushless DC motors not only perform better than variable reluctance motors but also scale better, offering the highest power density at the expense of stringent requirements on materials. With the manufacturing process under consideration here, it is possible to process and shape the required materials for brushless DC motors and therefore build a high performance motor in the millimeter or sub millimeter scale.

Motor geometry: The basic motor design consists of stator, rotor and armature coils. To avoid problems with attaching the propeller to a thin shaft, the rotor sits on the outside and rotates around the stator (see Figure 6). The stator plates fit in between the copper cages (used as armature coils) and guide the magnetic flux to the air gap between themselves and the rotor on the outside. The rotor has several keys on its outside where the propeller will be attached with either press fit or with a low viscosity adhesive. The motor must be easy to attach to an airframe and must drive a propeller that is many times its size. The copper cages that form the armature coils will be bonded to pads on the main frame structure, where they are connected to the motor control circuitry. The copper disk connecting the studs is also used to keep the rotor in its vertical position. Extrapolating the power density from commercially available miniature motors we expect to get about 1 W/gram maximal mechanical power. Different power and torque levels can be easily obtained by up or down scaling existing micro motor designs.

Fabrication: Our technique for fabricating a mesoscopic motor takes advantage of the high degree of refinement in silicon processing technologies combined with Electro Discharge Machining (EDM). It is essentially a molding and casting process. The master molds are made with standard VLSI lithography and plasma etch technologies. Where at the macro scale one might fill molds with molten metal, at this scale the molds are filled with copper by electroplating. After the molds are removed the copper parts are either used in the final assembly or used as EDM electrodes to shape parts in their final materials. Details of the processes are described on the following page.

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2 Deng, Keren, "Outer-rotor poly silicon wobble micromotors", Sensors and Actuators v 64 n 3, 1998
**Armature coil or copper cage**

*Mold*—A silicon master mold is made using conventional VLSI lithographic and plasma etch processes. Since copper doesn’t adhere well to silicon the mold is first sputtered with a layer of titanium and then with a seed layer of copper.

**Electroplating**—The copper-coated mold is connected to a negative electrode and immersed in an electrolyte solution. It is electroplated until the cavities are filled. Care must be taken that the narrow passages in the mold do not fill up before the entire mold is filled.

**Remove Silicon**—The entire silicon-copper mold assembly is boiled in KOH, which removes the silicon, leaving the final copper part. As in casting at the macro level, some finishing may be necessary on surfaces where the mold cavity was open.

**Stator plates**

*Mold*—To fabricate a stator plate a silicon mold is first made as above. This time the mold is made with the positive shape of the part since the stator plates’ final shape will be produced by the EDM process from a copper electrode. The silicon mold is sputtered with titanium and copper.

**Electroplating**—The copper-covered silicon mold is electroplated until its cavities are filled with copper. The stator mold is shallow in relation to its width, and therefore relatively easy to fill.

**EDM Electrode**—Before the silicon is removed from the assembly the copper half is soldered to a blank EDM electrode. The removal of the silicon leaves a negative copy in copper of the stator plate. The electrode is mounted in the EDM machine with a thin sheet of amorphous metal (the same thickness as the Stator Plates) and the excess amorphous metal is removed.

**Coating**—The amorphous metal stator plate is then sputtered with teflon or another insulating material to insulate the plates within the stack. This will also reduce friction in the motor assembly.

**Motor rotor**

*Mold*—The process for making the rotor is essentially the same as that of the stator plates: A mold is made in silicon with the positive shape of the rotor. The mold is sputtered first with titanium and then with a seed layer of copper.

**Electroplating**—The copper covered mold is electroplated until the mold cavity is filled with copper.

**EDM Electrode**—Before the silicon is removed from the assembly the copper half is soldered to a blank EDM electrode. The removal of the silicon leaves a negative copy in copper of the rotor. The electrode is mounted in the EDM machine with a piece of FeCrCo and the excess material is removed.

**Magnetize**—The FeCrCo rotor is then magnetized before assembly.
Airframe structure

We plan to evaluate tradeoffs between a six motor versus a four motor design. Fewer motors simplify control logic, redundancy of six motor version improves payload and probability of mission success. The airframe structure is designed to carry the mesomotors, battery, electronics, and other payload. A preliminary proposed airframe is a hexagonal shape with maximum payload area in the center as shown in Figure 8. Six circular bases for placing motors are located at the corners of hexagon connected with outer struts, lines of the hexagon. A center base for battery and other payloads is an area with the minimum interference with rotors of the mesicopter. This area physically connects with the centers of the outer struts. Multiple layers of battery can be deposited on one side of the airframe surface in order to obtain the required power, while the circuitry will be fabricated on the other side of the structure. The cross section of the struts is initially designed to be square. An optimum design of the cross section will be decided in the first six-month period.

The analysis and design of the mesicopter rotor will involve three basic tasks: airfoil design, 3-D rotor design, and an investigation of unsteady aerodynamics for enhanced performance. Since rotor performance is strongly related to the maximum lift that the airfoil section can generate and because airfoils at this Reynolds number have very limited lifting capability, high lift laminar section design is an important part of the rotor development. An inverse design technique based on a separation free, maximum gradient pressure distribution will be used to generate initial airfoil sections. This will be followed by Navier-Stokes analysis and subsequent refinement of the geometry.3

Figure 9. Side view and top view of solid model for initial rotor blade design.

An approach to optimal rotor design in this viscous-dominated flow regime is currently being developed. The analytic theory extends the work of Larrabee4 on optimal inviscid propellers and Adkin’s5 incorporation of viscous drag to properly include the Reynolds-number dependent section properties in the initial rotor sizing, twist, and chord distribution. This work will be augmented with a more refined analysis code coupled with nonlinear optimization. In this way, complex section characteristics obtained from the first part of the work may be incorporated into the design process.

If one relies on simple steady laminar aerodynamic theory, it may be argued that bumblebees cannot fly. That they indeed can, suggests that significant advantages are potentially available by exploiting unsteady aerodynamics in this Reynolds number regime. Like the bumblebee, the mesicopter’s performance is limited by section maximum lift (although computations suggest that the power available is sufficient for flight even without this effect). We propose to investigate the extent to which this concept may be utilized with very small rotors. At these small scales, it is possible to produce rather large changes in angular rate introducing vortex shedding in a manner similar to that obtained by rapid changes in angle of attack.6 The concept will be studied briefly by theory and by subsequent experiments.

Mold Shape Deposition Manufacturing (Mold SDM) will be considered as a fabrication technique for the rotor blades. Mold SDM has been used at RPL to fabricate a wide variety of ceramic and polymeric parts. It is capable of fabricating parts in the size of the mesicopter’s rotor. Since small devices are relatively stiffer than large devices, a wider variety of materials can be used in small scales than in large scales. Therefore the materials selection is mainly influenced by the compatibility with the fabrication technique. First experiments have shown that materials used in Mold SDM (ceramics and polymers) are suitable for being used in small scales. In Figure 15c, ceramic blades (green part) are shown which have been made using Mold SDM. The feature size of the blades is comparable to the feature size of the airfoil shapes necessary for the mesicopter rotor blades.

The mesicopter has limited space and weight-carrying capability for the power source. Therefore, it is imperative that the energy and power requirements be defined as early as possible in the development program to enable the appropriate choice of battery chemistry and battery design for a set of mission requirements. This is the primary objective of the first six month’s effort. A very conservative battery design assumes significant packaging and interconnection weight penalties. .2 g high power lithium ion cell running at 125 watts/Kg at 3.0 volts (average) will require a 20 layer cell stack providing ~45 Wh/kg specific energy. This battery should provide in excess of 150W/kg average power with a mission duration of at least 30 minutes. The overall volume of this battery, unpacked, is 62 mm³. This battery will be rechargeable and provide a good test bed for the mission requirements. We will then switch over to a lithium metal system to provide higher specific energy, but lower power capability. Using such a battery with similar dimensions, should lead to a mission duration of up to 50 minutes. When oganodisulfide/elemental sulfer cathodes become available, the mission length can be further extended to 1.5 hours.

Management Approach
The management plan of the proposing team builds on existing working relationships of a number of team members and laboratories. Fritz Prinz and Ilan Kroo will be Co-Principal Investigators for the initial phase of the work. Subsequent phases will require more coordination, particularly with our industrial partners. John Fessler will coordinate input from the aerodynamic research team with progress regarding fabrication and testing. The team will be assisted by Paul Losleben of the Stanford Nanofabrication Facility to coordinate task planning and provide guidance for the practicality of semiconductor fabrication methods for mesicopter production. Ilan Kroo, John Fessler, Paul Losleben and Fritz Prinz have joint ongoing research projects for the design and fabrication of a spectrum of state of the art devices including the use of SFF and VLSI fabrication techniques to explore miniature flaps for flow separation control on next generation aircraft wings.

A web-site will be established for the overall project and will be used as a convenient reporting mechanism. Progress on each task will be updated to reflect new events as they occur. Results are expected to be reported at annual Fabrication and Aero Design conferences.

A more detailed management plan will be developed during the initial phase of the proposed work including a description of our proposed relationship with SRI and MDOT corporation.

Personnel
For the initial phase of the project Profs. Ilan Kroo and Fritz Prinz will serve as Co-Principal Investigators and will direct the work of the research associate and two doctoral students who will serve as research assistants. Subsequent phases will involve our industrial partners at MDOT and SRI; their background will be described in detail in the proposal for subsequent phases. Short biographical sketches of the P.I.’s are provided below.

Ilan Kroo: Professor, Dept. of Aeronautics and Astronautics, Stanford University

Education
B.S., Physics, Stanford University, June 1978
M.S., Aeronautics and Astronautics, Stanford University, June 1979
Ph.D., Aeronautics and Astronautics, Stanford University, June 1983

Professional experience:
Professor, Department of Aeronautics and Astronautics,
President, Desktop Aeronautics, Inc., an aeronautical software company
Government review, evaluation team member for Tier II+, Tier III- UAV programs for ARPA
Consulting in aerodynamics and aircraft design for Boeing Commercial Airplanes, Failure Analysis, Aero Vironment, Americas Cup Syndicates, Directed Technologies Inc., Alliant TechSystems

Awards.
San Francisco Section AIAA Young Engineer of the Year, 1982.
Societies.
NASA Special Achievement Award, 1985.
Misc. Info:
AIAA Lawrence Sperry Award, 1990.
Grand Award Winner, Popular Science Best of What's New 1992, SWIFT.
Outstanding Teacher Award, Stanford Aero/Astro Dept. 1994.
AIAA Tech. Com. on Multidisciplinary Design Optimization, 1995
Member Editorial Board for Aircraft Design, Elsevier Press.
National Research Council Committee on Uninhabited Air Vehicles.

Selected relevant publications

Fritz Prinz
Rodney H. Adams Professor of Engineering
Department of Mechanical Engineering, Stanford University

Education
Ph.D., Physics, University of Vienna, 1975

Professional experience
1987-1994 Professor, Department of Mechanical Engineering, Carnegie Mellon University.
1995-1997 Chairman, JTEC/WTEC Panel on Rapid Prototyping in Europe and Japan
1994-present Rodney H. Adams Professor of Engineering, Stanford University. Member Departments of Mechanical Engineering and Materials Science and Engineering, Co-Director of Stanford Integrated Manufacturing Association (SIMA)

Awards
1991 Sir Christopher Hinton Lecture, Royal Academy of Engineering
1991-1992 Engineer-of-the-Year, ASME, Pittsburgh Section
1996 Elected Austrian Academy of Science, Vienna, Austria
1997 Boardmember, National Research Council Committee: Design and Manufacturing

Selected publications
**Prior Work**

Prior work has been done mostly related to mesomotor fabrication. The same methodology is applicable to other parts of mesicopter manufacturing.

![Figure 10](image) Non-through etching patterns  
![Figure 11](image) Cu coils (8 studs copper cage)  
![Figure 12](image) EDM Cu electrode for rotor.

A conventional silicon process including lithography and plasma etching was applied to create mesoscopic patterns in a silicon wafer. These patterns are then used as masks in electroplating process. According to the needs of these patterns, two different etching levels are processed—through-etching and non-through etching. Through etching provides patterns for through-hole electroplating. Fine and detail geometry can be achieved through this technique. The straight through-holes have only one-degree error between the top and the bottom surfaces. Non-through etching patterns are used in creating copper electrode for Electric-Discharge Machining. By incorporating the EDM process, the mass-productive fine patterns can be transferred to other engineering materials without confinement of only silicon-based materials. An example of non-through plating pattern for stator plates of motor is shown in Figure 10.

**Electroplating** in our application is mainly used to create copper coils of the motors and copper electrodes for electrical-discharge machining. A commercial acid copper electroplating bath was used. Pulse-Reverse plating currents were found to be the best approach to obtain dense and nearly void-free copper, especially for the high aspect-ratio application such as coils of motors. Figure 11 shows a plating result of 500 micrometer high copper coils. A through-etched silicon wafer was used as mask for electroplating and was removed afterward. Copper electrodes are built by electroplating as well. A thin layer of copper was sputtered on to the non-through-etched wafer as a seed layer for electroplating. Figure 12 gives an example of EDM copper electrode pattern transferred from patterns on the wafer.

**Electric-discharge machining (EDM)** is capable of shaping arbitrary conductive materials and expands the materials range of our process far beyond conventional MEMS materials. Soft magnetic materials like silicon iron or amorphous metal were shaped in the RPL to serve as components for permanent magnet excited DC meso motors (Figure 13). By refining the EDM process the surface roughness has been improved significantly in the last months. (Figure 14)

![Figure 13](image) Stator plate  
![Figure 14](image) Improved smoothness for stator plate
SDM (Shape Deposition Manufacturing) and Mold-SDM processes developed in the Rapid Prototyping Lab at Stanford University were able to build parts in metal, ceramics, and polymers. A 7mm-diameter propeller was made of nickel (Figure 15a) with SDM methodology. Fabrication technologies consist of electroplating, CNC machining, and EDM. Figure 15b shows the variety of size of ceramics turbines that could be achieved through Mold-SDM. The molds for 24mm and 6mm diameter turbines were built of wax, while the molds for 4mm turbines were made out of silicon. These techniques will be useful in manufacturing mesicopter rotors. In Fig. 15c ceramic blades are shown that have been cast into micromachined molds. They show that Mold SDM can be used to fabricate parts when features are too small to be machined conventionally. By combining micro-machining (e.g. plasma etching of silicon) and conventional techniques, Mold SDM is capable of fabricating parts in a wide range of sizes.

Small Aircraft Development Experience: The Aircraft Aerodynamics and Design Group at Stanford has been involved in the development of a number of small UAV’s for aerodynamic and control system design research. In collaboration with NASA Ames Research Center, we designed, developed, and tested an actively-controlled oblique all-wing configuration in 1994. With support from McDonnell-Douglas, a tailless, blended-wing-body flight control testbed was designed, built, and tested at Stanford in 1997 and we are currently working with Boeing on the development of a 10-ft span tilt-wing vehicle. These aircraft included stability augmentation systems and were designed to gather data on vehicle aerodynamics and flight dynamics. In addition students in our group and related research groups in the Aero/Astro department have been involved with robotic rotorcraft, developing and winning the AUAV Aerial Robotics Competition with an autonomous, GPS-based helicopter in 1996.

Facilities and Equipment

Most of the micro-machining necessary for this project will be done in collaboration with the Stanford Nanofabrication Facility (SNF). The heart of SNF (Figure 16) is 10 500 sq ft of class-100 clean-room, which is equipped with state-of the art equipment necessary for fabricating micro-electronic and micro-mechanical devices. The equipment includes several steppers and aligners for lithography and spin-coaters and developers for resist-processing. Crucial for this project is the plasma etching of silicon. This will mainly be done on a STS Multiplex Deep reactive ion etcher. The machine is capable of etching 4

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m/min at a very high anisotropy (angle of sidewalls >89.3°). All in-process characterization (measurement of film thickness, wafer characterization, ...) can be done at SNF with the available microscopes, profilometers and ellipsometers. SNF is also equipped with a wide variety of thin-film deposition systems (chemical vapor deposition and sputtering).

The Rapid Prototyping Laboratory (RPL) at Stanford University, shown in Figure 17, has created a facility for Shape Deposition Manufacturing (SDM) of ceramic and polymeric parts.

The station consists of a Haas VF-0E 3-axis CNC mill onto which two deposition heads for wax and solder mask are mounted. The station also includes an UV-light for curing the solder mask and an infrared-light for preheating the substrate. This station will mainly be used to fabricate large and medium-sized parts. RPL is equipped with a 5-axis CNC mill (MAHO MH 600-C) and a 3-axis electro-discharge machine (Moldmaster M45-B). The EDM machine is crucial for replicating copper-patterns into magnetic material. The machine is suitable for manufacturing small features (<100 µm) as well as parts larger than 100 mm. For machining of small features it has been equipped with a current-reducing head.

Since access to SNF is limited to clean-room-compatible materials and devices, RPL has built up its own mesoscopic laboratory where all the materials can be processed which are not allowed at SNF. RPL’s meso-lab is equipped with a vacuum chamber suitable for reactive AC- and DC-sputtering. Through the Department of Materials Science, RPL has also full access to a wide variety of characterization (SEM, EDX, X-ray diffraction) and testing equipment (tensile testing, fracture toughness, mechanical properties of thin films).