Field Fabrication of Solar-Thermal Powered Steam Turbines for Generation of Mechanical Power

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FIELD FABRICATION OF SOLAR-THERMAL POWERED STEAM TURBINES FOR GENERATION OF MECHANICAL POWER

by

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Submitted to the program in Media Arts and Sciences,
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ABSTRACT

Providing adequate energy to developing countries is one of the greatest global technical challenges today. Fabrication is undergoing a revolution that parallels the digitization of computation and communications. Emerging affordable, "desktop" fabrication tools are providing the precision and repeatability necessary for regular people to design, manufacture, and install a system to convert solar thermal energy to useful work. In the spectrum of devices that use solar energy, this field-fabricated system exists in a space between crude solar cookers for heating food and complex, expensive photovoltaic cells. Computer control and high precision allows regular people to experimentally converge on a locally-appropriate design and implementation to solve the challenge of providing energy.

This thesis describes a field producible, small-scale turbine that uses solar thermal energy to provide mechanical energy. I investigate a solar thermal steam-driven turbine system and build and evaluate several versions in field fabrication lab locations around the world. I consider the efficacy of deployment in rural developing areas.

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THESIS READER: John M. Deutch

John Deutch is an Institute Professor at the Massachusetts Institute of Technology. Mr. Deutch has been a member of the MIT faculty since 1970, and has served as Chairman of the Department of Chemistry, Dean of Science and Provost. Mr. Deutch has published over 140 technical publications in physical chemistry, as well as numerous publications on technology, energy, international security, and public policy issues.

Professor Deutch's research applies statistical mechanics to equilibrium and time dependent problems in physical chemistry. Emphasis is placed on developing techniques that permit the quantitative understanding of a wide variety of phenomena. Three distinct areas of research are under investigation.

One area is the theory of dilute and concentrated polymer solutions with attention placed on understanding the frictional properties of these solutions, for example, diffusion and viscous flow. Recent efforts have been directed to modeling the solution as fluid in a porous medium; to investigating polymer behavior in constrained spaces, such as, pores or thin films; and to applying the renormalization group technique to polymer problems.

A second area of interest involves two-dimensional chemistry. This work includes study of the chemistry that takes place in constrained environments such as at fluid interfaces, inside cells, and in liquid crystal solvents, where the environment influences both the equilibrium distribution of particles and their dynamic motion. Most recently, a theory has been developed to predict the equilibrium shape of lipid bilayers (both on surfaces and in three dimensional vesicles) based on the competition between surface tension and dipolar forces.

The third area concerns the theory of diffusion controlled reactions. Here the interest is in studying situations that arise frequently in practice but are not correctly described by conventional theory. A specific example is the enhancement in chemical rates that can be realized by modifying the dynamical pathways available for reactants to find each other.

In recent years, John Deutch's research interests have turned to physical chemistry and energy technology. Currently a major project is underway to analyze and model fuel cell behavior including technical, economic, and environmental aspects of these systems. A comprehensive interdisciplinary faculty study of the future of nuclear power has recently been and a follow-on faculty study on the future of coal (including CO_2 capture and sequestration) is underway.

Read by: ______________________________

John Deutch
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THESIS READER: Alexander H. Slocum

Alexander H Slocum is Professor of Mechanical Engineering and MacVicar Faculty Fellow at MIT. His research projects range from consumer products (e.g. cameras and printers) to the machines that make them (e.g., diamond turning machines and wafer steppers). His main area of interest is precision engineering - the ability to precisely control motion - which is critical to the success of any manufacturing based economy. He teaches courses 2.007 Introduction 2 Design and 2.75 Precision Machine Design.

Among the numerous awards and prizes Slocum has received are 9 R&D 100 Awards for scientific product developments, SME's Frederick W. Taylor Research Medal, the Martin Luther King Leadership Award, and he was the Massachusetts Professor of the Year (2000). Alex has over 5 dozen patents with more on the way. He is also a member of the American Society for Precision Engineering, the American Society of Mechanical Engineers and the Society of Manufacturing Engineers.

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Considering a bottom-up, decentralized, thermo-mechanical approach to solving the world's energy problems can only take place at this strange place called the Media Lab at MIT. Here I am surrounded by supportive, inspirational, and crazy people who persist in spite of the (perceived) absurdity of their projects. Their ideas, encouragement, assistance, and enthusiasm have led me to develop and understand my relationship with world as an engineer. I am indebted to too many to name and describe; in addition to the past and present members of Physics and Media (my research group), I found at this wonderful place in particular,

Kenneth Cheung and Amon Millner who both volunteered ridiculous amounts of competent help in the execution of these experiments and other tangential adventures. The time, energy,and committed-ness they willingly offered was of an enormity unreasonable to ask. I am inexpressibly grateful.

Ara Knaian who patiently led me through thermodynamics (and nearly any other engineering topic) and continues to be a conduit for expressing the dynamical physical world in terms that can be evaluated with proper engineering rigour.

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Issac Chuang, without whom this adventure never would have began.

and,

Neil Gershenfeld, my advisor, who practices *ready, fire, aim* with such profound brilliance that I cannot but be left grinning stupidly happy.

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Introduction

Challenge

Providing adequate energy to developing countries is one of the greatest global technical challenges today. An individual's ability to produce electrical power in developing rural areas is restricted by the economic limitations of importing energy production machines such as generators and the constant need for input fuel. Solar energy has great promise as an input source because it is widely distributed around the planet and has high energy density. The current practice for solar energy usage in rural areas is the purchase of photovoltaic systems which are expensive to produce and require specialized silicon fabrication processes. Rural inhabitants need to be able to fabricate solar energy conversion machines locally to reduce dependence on supply sources and the energy must be produced at a lower cost than what is available.

I once traveled to a rural village in Western India to work with technical students finding solutions for local problems. I brought with me some neat equipment, all of which ran on the wrong voltage. Power was primarily provided by a diesel generator, which required diesel, a valuable commodity. My eyes were opened to the crippling effects of not being able to plug into anything. I was severely restricted in problem solving because I was limited to solutions without computation complexity. There were few text books or print resources to turn to, and they were difficult to search. Hand-tooled mechanisms were crude and imprecise. Computation, communication, and fabrication all hinged on the availability of electrical power. Without that generator, I felt like I could get nothing done. Since then, over and over again, I've traveled with more and more interesting equipment to more and more interesting places and each time I stood frustrated, holding a plug with no outlet to plug into.

In Ghana, a small nation in West Africa, two large dams in the north at Lake Volta produces 1.1 GW of electricity, but the transmission infrastructure reaches only about one-quarter of the nation's households so the rest of the country still relies on deforestation – burning everything they can find. A tribal chief from a very small north-eastern village asked me, "what else is there?" Ghana is an equatorial nation just one degree north of the equator. I stood in the middle of that tropical jungle and looked around. Lush, verdant vegetation grew nearly before my eyes under the kilowatt per square meter from the sun which baked the ground. I felt the steady six to eight meter per second in-land breeze and heard several strong flowing waterways and access to ocean tides. Of these natural and renewable resources, the chief wanted to know what could be done with the sun, the most abundantly available resource everywhere in Ghana. Photovoltaics are much too expensive for widespread use, here the annual per household income is just over $2,000. Aid workers brought solar cookers but they are used just for cooking. What application of technology could address the need for rural energy?

Solution

For $50,000[1] today, you can place fabrication capabilities in the field that have micrometer machining precision, microsecond control loop response times, and computational complexity on the order of giga-FLOPS[2]. Access to microns, microseconds, and giga-FLOPS allow people to design, optimize, fabricate, and evaluate devices of a complexity that is too difficult and tedious to do by human brain alone. The current collection of machines loosely represent what is now "personal fabrication". Today's bundle of disjoint commercial machinery and software will become desktop *fabrication*. Just as when mainframe computers and typesetting machines gave way to desktop computers and desktop printers, in time, desktop fabrication will become individually affordable and user friendly.

The coming widespread availability of affordable digital fabrication tools paves the way for something as complex as a steam turbine to be made in the field. Micron-precise fabrication tools and modest desktop computers to drive them are deployed in the field and enable the design and construction of alternative solar energy devices, expanding the range of solar resource options. This thesis describes a solar-powered steam turbine to convert solar thermal energy to useful work. It is an experiment that shows the feasibility of devices which lie in the largely unexplored space between crude solar cookers for heating food and complex photovoltaic cells for narrow spectrum conversion to electricity. A turbine system can be manufactured in field fab labs by local residents and in doing so they can

[1]USA 2006 dollars; see http://fab.cba.mit.edu/ for fab lab inventory list

[2]"FLOPS" is floating point operations per second. It is a measure of a processor's performance. More FLOPS means a faster processor and therefore allows more complex computation in less time. A moderately inexpensive Pentium 4 computes on the order of a few giga-FLOPS (GFLOPS). Comparatively, a person calculates on the order of one FLOP (plus a whole lot of complaining).

address immediate energy needs as well as continue to grow and expand their energy system. The successful implementation of small solar-steam driven turbines leads to consideration of a mechanical energy economy driven by solar availability.

The solar thermal steam-powered turbine energy system uses a parabolic collector to concentrate sunlight heat to a boiler. The boiler converts water to steam which exits the boiler at a higher pressure and velocity than the water. The steam acts on a turbine which provides rotational mechanical force. The rotational shaft work can be coupled to those things that require energy – pumps, compressors, grinders, and generators. All components of the system can be made and assembled by regular people in a field fabrication lab. Because the users have access to the designs and the fabrication tools, they are able to experimentally optimize the design to meet changing conditions and needs.

Motivation

I came to the MIT Media Lab as a defense engineer, devoted since childhood to putting the best technologies in the hands of our nation's servicemen in their pursuit of security for American citizens. I believed, and still do, that American soldiers should carry with them tools that are easy to use, don't break, on which they can entrust their lives, and are better than everyone else's. These systems can always be made a little better, improvements measured in ever-smaller time or weight units, so that defense research lives on the bleeding edge of science and manufacturing capabilities. When I began to share with others the joy of a career in making things and solving problems, I found that many people (especially students) lacked basic understanding of fundamental engineering principles. Once introduced to these ideas, students would rocket into frenzied design-build-evaluate-redesign cycles as they experimentally discovered the world. I also quickly realized that much of the underserved first world and underdeveloped third world lacked *access* to basic engineering concepts and old ideas from the time man became industrialized. It became clear to me how necessary it is for people to speak openly with each other about ideas and share knowledge. The great divide isn't to have or have-not, it's knowing about the thing at all.

I took leave from defense engineering to travel the world and bring a startling concept where I go. It is a crazy and premature idea that has potential to change the way the world thinks about technology consumers and producers, and even where the riches of the world lie. I ventured out to find the special places and people that share my passions and unending hope in people, finding applications for technology and learning about the social and community needs that go hand in hand with development. Several labs around the world now comprise a limited experiment including dry dusty rural India, a shipping port in Ghana, an Apartheid-era township in South Africa, coffee-growing high mountains of Costa Rica, Arctic sheep and reindeer valleys in Norway, and even inner city Boston. It is an exciting modern day version of trekking off into the jungle with crates and crates full of sensitive equipment in Dr. Livingstone style, and it's very cool. (The multitudinous biting insects and heat are probably still the same.)

In the course of two itinerant years, my focus shifted from the engineering details of energy conversion and mechanisms to the social and individual implications of making complex, high precision devices in primitive places. This thesis is a partial, mostly technical, description of my experiences building solar and wind energy conversion devices in primitive and remote places in the world. Early on, I mistakenly believed that I was embarking on an engineering project with some broader consideration for energy policies. I was genuinely surprised to discover my greatest impact is to address the crippling lack of world-wide application of technology for peaceful and humanitarian goals.

Background

Energy

Proper consideration of energy topics include policy, economics, technology, and analysis. I conducted technical research for deployment in developing nations with emergent energy policies that are difficult to study. This thesis does not provide policy suggestions or energy plans from a national view but instead considers an alternative, decentralized approach to converting local energy to usable energy.

Fire provides heat and light. Animals provide mechanical energy. Fire and animals were nearly the entirety of man's energy portfolio until the invention of the steam engine which converts heat energy to mechanical energy. Access to energy leads to a better quality of life. In places where there are no alternatives, the motivation for creating energy conversion devices is simply to have energy rather than the displacement of less desirable fuel sources.

If we could pretend that energy resources are distributed equitably around the earth then calculate the extractable energy available on any one acre in one year, fossil fuels are the big winner. In table 1, I don't take into consideration the energy required to extract or process the energy into usable energy.

wind	3.42E+04	Wh-e[3]	
solar (total)	2.41E+10	Wh-th[4]	
solar (available to PV)	6.08E+08	Wh-th	
corn into ethanol	2.20E+06	Wh-th	
switchgrass into ethanol	2.70E+07	Wh-th	
algae into biodiesel	4.11E+08	Wh-th	
natural gas, shallow	1.28E+04	Wh-th	in one foot depth
natural gas, deep	6.74E+07	Wh-th	in one mile depth
coal, shallow	4.50E+09	Wh-e	in one foot depth
coal, deep	2.38E+13	Wh-e	in one mile depth
oil	**1.57E+18**	Wh-th	

Table 1: Extractable energy available on any acre of the earth in one year

[3]Wh-e means electrical watt-hours
[4]Wh-th means thermal watt-hours

The reality is that oil and coal resources are unevenly distributed in the world. To electrify their countries, many governments must compete with other consumers and negotiate with foreign export sources or find technologies that utilize domestic, renewable energy sources. To repay the capital cost of building large, centralized energy plants, promotional incentives are often employed to artificially inflate a user's electricity needs. These electricity usage behaviors learned in the start-up period of a plant's operation can lead to long term unnecessary habits that drive energy consumption beyond a nation's means and contribute to airborne pollution.

The system efficiency for electric lighting from a centralized coal-fired plant is as low as 1.3%. The generation of electricity at the plant, transmission of electricity, and electrical to incandescent light conversion comprise the major losses. [Fowl] Centralized energy systems lose more than 50% of heat from industrial processes that could be used in cogeneration. In the case of renewable resources, hydro-powered electrical generation has a huge advance in that the water source is generally not as intermittent as sunlight or wind. At the Hoover Dam in Nevada, highly efficient Francis-type turbines at the base of the dam are used to generate electricity. Power lines bring the electricity from the bottom of the dam to a substation at the top of the canyon where the electricity is upgraded for transmission to California, Utah, Colorado, New Mexico and Arizona. Because the quality of the signal degrades over long distances, along the way the power is routed through several subsystems where it is re-upgraded and conditioned. Finally, a substation near the point of consumption downgrades power to for delivery to households. Although the Francis-type generator is approximately 90% efficient[5], substantial losses in the transmission system make the entire system less than 50% efficient.
Power should be generated close to where it will be consumed in a distributed rather than centralized scheme. Decentralized systems have an inherent feature in that the malfunction of one small plant among many small plants is less catastrophic than if a single equal capacity plant were to malfunction. Smaller plants can also respond more quickly to shifting load needs and thus lose less to lost overproduction. A nation's potential CO_2 emissions is significantly reduced simply by not overproducing power that will be lost in transmission or storage.

[5]Data on turbines from GE Energy, http://www.gepower.com/

A great deal of energy is used for heating and mechanical work. In the United States, heat is the desired end product of energy approximately half of the time and mechanical energy is the desired product about one quarter of the time [Fowl]. I consider an alternative energy system based on decentralized conversion of available fuels to generate energy in its most needed forms: heat energy to cook food and drive cooling for refrigeration, mechanical shaft work to perform daily tasks of grinding, plowing, and pumping. Electricity is needed only for computation and lighting and possibly instrumentation.

Energy Scheme for Rural Villages

The fastest growing market of solar energy technologies are the third world countries like Ghana with abundant sunlight and a population currently without electricity. Ghana receives 4-6 kWh/ m^2 per day and a cumulative 1,800 to 3,000 hours of sunlight per year. Solar radiation is highest in the north of the country which is also the most rural (many villages here do not have a single phone). Developing nations without existing centralized infrastructure can benefit from employing the best of a century of electrified technologies without being saddled with backward integration concerns. As new homes are built in rural areas, they can take advantage of advancements in low energy consumption products and architectural designs for passive management of space heating and cooling.

In the conventional view, third world countries regard energy as food and heat, something gathered and consumed while developed nations view energy as a commodity – energy is measured, stored, purchased and traded. The industrialized energy economy is built around the movement of electrical energy because electrical energy is easily transported and measured, and can be easily converted to mechanical work or heat [Ruedisili]. The centralized energy creation scheme appears to work because the conversion from heat to electrical energy can be efficient at larger scales where output heat can be reused. However, cumulative efficiency of the system must take into account the entire electrical power infrastructure including unused electrical losses, source fuel transportation, and waste disposal. A decentralized approach to providing on-demand energy for rural homes requires a scheme for energy storage. This is especially true if the input source is solar, wind, tidal, or any non-constant force. Storage capacity must be at least equal to the consumption expected when the sun is below the horizon or winds shift because of local weather. Commonly, rechargeable batteries are used to store electrical energy generated when the sun or wind is present then discharged as the user requires. Batteries are convenient – they are dense and mostly quiet, but do not hold charge indefinitely. Nickel-metal-hydride (NiMH) batteries, the most environmentally (and people) friendly rechargeable battery type used in household photovoltaic systems, discharge a few percent per day at 70 °F, a temperate daytime temperature. In hot climates (86 °F – 104 °F), a NiMH battery will self-discharge in one to three months, and in very hot climates (104 °F – 122 °F) or if the batteries are stored in a space which traps heat, a NiMH battery will self-discharge completely in less than a month [Quest]. The batteries must be cycled (discharged completely and charged completely) every few months or more, and they lose their ability to be charged over time. The biggest drawbacks to most batteries are their cost, toxic chemical make up and inability to be locally manufactured at the point of use.

An alternative scheme for energy storage is $m \cdot g \cdot h$, or potential energy. Pumping water uphill, lifting weights, and coiling a spring mechanically store energy for later release. Hydroelectric generation from dams are an extreme example of obtaining electricity from potential energy. Scaled to individual households, this takes the form of pumped storage of water to large water tanks on roof tops. The water isn't consumed, it can be collected in an underground or ground-level tank then pumped back to the rooftop when the energy source resumes.

Importantly, when a household or village outgrows its existing capacity, it gains more capacity by making more conversion devices instead of cutting down more forests. The community's ability to fabricate their own energy devices means access to usable energy without trading their air quality, future resources, or being forced to move closer to cities. The start up rate is much more timely, and rural villager don't need to wait for others to bring, or fund, development to them. Local self-reliance at an initially reduced capacity can be a desireable option as opposed to a two year wait and $15M cost of a 1 GWe coal plant.

Energy production is still most sorely needed in the field. Energy producing machines must be fabricated in the field for the best use of resources, local and overall costs, and long term sustainability.

Measuring available solar energy

To evaluate system efficiency, it is necessary to measure the input energy. In the system I describe, heat from the sun is the sole source of input energy. Solar radiation, or the radiant energy emitted from the sun, that hits the earth is a function of the distance between earth and the sun, the condition of the atmosphere, and the latitude of the measurement. Solar irradiance is usually measured with a pyranometer (broad, direct and diffuse contributions of heat) or a pyrheliometer (incident light only). Both meters use a thermopile that converts temperature to voltage. A decent pyranometer costs aproximately $500.

Instead, I used a $20 light meter sold for photographers to find an approximate value for the input energy. The meter reads aggregate light intensity in *lux* (lx), the units of irradiance.

$$1 \text{ lux (lx)} = 1 \text{ lumens (lm)} / \text{m}^2$$

To convert from *lux* to *watts*, we have to take into account the different conversion factor for every wavelength from lux to the radiometric unit (watts/m^2). Direct sunlight is known to be on average 93 lumens / watt.

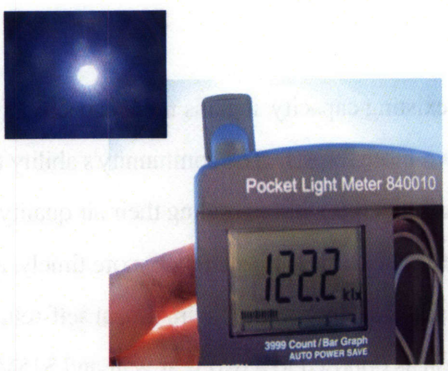

Figure 1: Measuring solar irradiance with a light meter.

In the high desert in Nevada where there is the little atmospheric obscuration, I measured direct sunlight to be 122 klx. On a 2.6 m^2 solar collector,

122k (lumens / sq m)(2.6 sq m)(watt / 93 lumens) =

3,410 watts total strike the reflector

or 1,311 watts per square meter

This value is just short of the 1,363 W/ m^2 – 1,375 W/ m^2 solar irradiance measured outside the earth's atmosphere over 26 years by geophysical data satellites.

Precision digital fabrication

Computers have become widespread and affordable and can be found in the most under-served and least industrialized parts of the world. Widespread desktop fabrication capabilities will follow shortly behind and soon everyone will have command of microns as well as microseconds [Fab]. Digital precision fabrication in the hands of nearly every person on the planet has huge implications and promises to change everything.

Part of what makes it possible to create complex devices in underdeveloped places is the degree of machine resolution available in "desktop" form and the availability of tiny, cheap microprocessors for machine control and computation. Cheap access to sub-micron length-scale machining and metrology as well as microsecond sensor-computation-response control loops allows us to construct devices on precisely the scale for humans to interact with the physical world. Materials at micrometer scale still behave classically and can be modeled as bulk materials. However, a micrometer is just below human perception resolution so finely featured contours can be created. Sub-micron precision fabrication equipment and metrology allows field users to work with state of the art commercial mechanical, electrical, and optical systems.

System	***Precision Required***
Precision **mechanical** parts that require "press-fit" tolerances	0.001" (0.0254 mm)
Smallest "surface mount" **electrical** components	0.01" × 0.005" (0.3 mm × 0.15mm)
Diffraction grating goove density for **visible light optics**	1 μm to 100 μm between grooves

Table 2: Resolution required for mechanical, electrical, and optical systems.

For $50,000[6] today, you can place fabrication capabilities in the field that have sub-micrometer machining precision, microsecond control loop response times, and computational complexity on the

[6]USA 2006 dollars; see http://fab.cba.mit.edu/ for fab lab inventory list

order of giga-FLOPS[7]. Access to microns, microseconds, and giga-FLOPS allow people to design, optimize, fabricate, and evaluate devices of a complexity that is too difficult and tedious to do by human brain alone. The current collection of machines loosely represent what is now "personal fabrication". Today's bundle of disjoint commercial machinery and software will become desktop *fabrication.* Just as when mainframe computers and typesetting machines gave way to desktop computers and desktop printers, in time desktop fabrication will become individually affordable and user friendly.

The final piece necessary for the revolution in making things is the digitization of fabrication. Imagine the cumulative propagation of small errors through something with a very large number of parts, say an Avagadro number (10^{23}). No matter how small we make the error, that tiny error is significant when amplified one hundred sextillion times. Conventional methods of design and fabrication limits complexity, mostly because we rely on the manufacturing machines to provide all of the resolution and placement precision. When communications and computation moved from analog to digital in the 1940s, we won increased complexity. Digitization offers the promise of increased complexity with predictable errors described as thresholds. Digital fabrication processes will use building blocks that locally code for global structure. Block assembly is fully reversible – the pieces can be take apart as well as assembled. Local coding, a geometric property of the block performs state restoration – so blocks placed far away from the origin have the same predictable errors as blocks placed near the origin. The assembler has error detection and correction, all together, this digital assembly process is the true promise for fabrication in the future.

Solar energy technology

Solar thermal energy delivers more than 3,000 BTU or 100 W to nearly every square foot on the surface of the planet. The commodity doesn't need to be electricity produced by a few and consumed by all. Instead the commodity can be the collection and conversion devices which nearly anyone can make in the coming years of personal fabrication.

[7] "FLOPS" is floating point operations per second. It is a measure of a processor's performance. More FLOPS means a faster processor and therefore allows more complex computation in less time. A moderately inexpensive Pentium 4 computes on the order of a few giga-FLOPS (GFLOPS). Comparatively, a person calculates on the order of one FLOP (plus a whole lot of complaining).

Solar energy is clean, widely distributed, and densely delivered as compared to other renewable resources. The sunlight that falls on just 2% of the Earth's surface is enough to meet the world's total energy needs (1998).

Current solar usage falls into three categories, direct conversion to electricity, thermal collection to generate heat or refrigeration, and thermal collection to generate mechanical work.

Direct conversion to electricity is most commonly accomplished with photovoltaic cells[8]. Photovoltaics (PV), which use only a small slice of the solar spectrum, are the most common example of rural home solar energy use but are expensive and inefficient for truly widespread use. Thermal collection usage for cooking, heating or refrigeration (through evaporative cooling processes) is the crudest form of solar energy and often found in various scales from dinner pot cookers, home heating, and mini-refrigerators. Thermal collection and conversion to electricity is mainly experimental and found only in the most industrialized countries where research is focused on large scale deployment in a centralized power generation scheme.

Solar motors have been described in history since at least the 1600's. Modern solar thermal engines typically employ complex engines such as the Stirling engine with hundreds of unique parts requiring true 3D machining and are nearly impossible to make in the field. While these engines are chosen for conversion efficiency, the operating capacity is greatly diminished due to frequent maintenance needs. Intrinsic complexity of the Stirling engines are also reflected in their price tag and build time.

Nikola Tesla's boundary layer engine, first patented in 1909, uses fluid to mechanically transfer energy to flat disks which are keyed to a shaft. These flat disks form the working surface of the engine and are significantly easier to produce than conventional curved and flaring turbine blades. The turbine can be scaled to micrometer lengths because adhesion, not impingement, causes momentum transfer between the moving viscous fluid with the disks.

[8]Shuguang Zhang, associate director of the MIT Center for Biomedical Engineering demonstrated in 2004 the ability to convert sunlight to electricity using a protein complex derived from plant chloroplasts.

How Boilers Convert Thermal to Kinetic Energy

A steam generator is a heat exchanger used to convert water into steam. The steam is a gas at much higher pressure than the water and the pressure can be converted into mechanical energy. Simply boiling water creates "saturated steam" which can recondense into water quickly. A boiler which further heats the steam creates "superheated steam" at much higher pressures. "Wet steam" is what is commonly seen coming from a boiling kettle and is actually a mix of water vapor and tiny droplets of liquid water.

A common steam engine uses the volumetric expansion associated with steam production to move pistons or turbines to perform mechanical work. An intriguing method of steam generation is to drip small amounts of water onto a very hot surface. The resulting "steam explosion" is due to the water flashing into steam very quickly.

Understanding Turbomachinery

Turbomachine is a generic term for a device which transfers momentum to and from moving fluids. Turbines and pumps are both turbomachines. Turbines take energy from moving fluids, usually a gas, and convert it to mechanical rotational "shaft-work" energy. Pumps do the opposite; they transfer mechanical shaft-work energy to the fluid which is usually a liquid.

There are three types of turbines, reaction, impulse, and drag. Reaction turbines use water pressure pushing on the turbine blades to produce motion and are an example of Newton's third law of motion that for every action there is an equal and opposite reaction. The water pressure changes as it moves through the turbine and gives up its energy. Because water stream will chose the path of least resistance there must be a housing to contain the water in the turbine. Reaction turbines are often used for medium and low head applications with high flow rates. Impulse turbines use the velocity of water hitting the blades causing the blades to move as well as changing the direction of water flow. Impulse turbines are an example of Newton's second law of motion which directly relates the rate of momentum change with the net forces acting on the turbine blade, in the same direction as the external force. Water velocity is the key driver so pressure must be converted to kinetic energy with a nozzle and aimed at the turbine. The impulse turbine is used in very high head applications. Drag, or fluid-friction turbines use the adhesion of fluid flowing past a rotor surface to drag the rotor into motion. Drag turbines are often used for very low head and high flow rates.[9]

The Boundary Layer Turbine

The boundary layer turbine operates differently than a conventional turbine. The working fluid drags on the rotor, causing momentum transfer by adhesion instead of impingement. This effect is most useful for low head and high fluid velocities fluids with low Reynolds numbers. Boundary layer turbines are very simple to manufacture, operates without high internal pressures, and tend to fail safely (rather than firing a blade projectile).

As fluid moves across a surface, the boundary layer is that first layer of fluid nearest the surface that is slowed by interaction with the surface. The boundary layer is a viscous force which can be thought of as arising due to fluid friction. The magnitude of the forces interacting between the fluid and surface are related to the viscosity of the fluid, represented by the fluid Reynolds number. At lower Reynolds numbers, viscous forces are dominate and the boundary layer is most effective at momentum transfer.

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[9] To use common African sights to illustrate the different ways these forces move objects: The force which powers a reaction turbine can be likened to a rhinoceros leaning against your back. You would move forward as long as the rhinoceros doesn't slip to the left or right around you. The impulse turbine is the cumulative effect of thousands and thousands of bullet-fast African biting flies diving Kamikaze style into your back, again pushing you forward. The flies only need to aim for you, but not worry about being constrained after they've hit. The cohesion, or drag turbine is the effect of a pack of cheetahs, the fastest land animal, running past you. The cheetahs come very close but divert before hitting your back, none of them hitting you in the back but the closer ones brushing against your sides and dragging you forward. The water "flow rate" is analogous to the mass of the animal and the water "head" is analogous to the speed that the animal is traveling. If we substituted a warthog for the rhino (lower flow, same head) or if the biting flies flew slower (lower head, same flow) you would be pushed in the same direction with less force. When it comes to the cheetahs, it's mainly their velocity that matters, a pack baby cheetahs would pull you along just the same as the Land Rovers full of hunters following them at the same speed.

The boundary layer turbine is an old idea. In 1913 Nikola Tesla patented a turbine based on the friction of fluid flow. It works because of the attachment at the boundary between the immovable, solid blade and the moving fluid. At the very interface between the surface and the fluid, some of the fluid must be slowed down by friction with the surface. The fluid just above the interface would be moving slight faster because it's tangling with something moving slowly. The fluid just about that would be moving slight faster still. If we plot the velocities of the fluid as a cross-section, it is roughly parabolic. This boundary layer is extremely small and usually ignored unless you're dealing with concrete pipes or something very rough, or a very viscous, thick fluid. Tesla's turbines exploits this interaction. The surfaces are shaped as discs about a shaft and as the fluid moves across the surface, it essentially drags the circular blade along with it. Overall turbine efficiency has been estimated at 95% [Tesla] and demonstrated at 41% [Rice] with a single stage and 70% with multiple stages.

The conventional wisdom is that bladeless turbines are inefficient compared to the simplest of paddle wheels. This is generally evaluated at the operating point suitable for paddle wheels – high head and variable flows. But bladeless turbines don't make use of all that pressure; the fluid shears and develops only a small adhesion region. The boundary layer system is more efficient at low flow pressures and momentum transfer efficiency increases as Reynolds number of the fluid decreases. A Tesla engine design can have as few as a dozen unique parts and requires only 2D machining, making it ideal for field production. In Tesla's time, the boundary layer engine was difficult to make because thin flat disks could only be made on a lathe where the force of the chuck holding the disk would cause large deformations. Metallurgy at the time was insufficient for high RPM, high temperature steam applications. Today, the bladeless boundary layer design is most often used as a pump for viscous, dirty, or difficult fluids. Recently, the bladeless turbine has been employed in applications where the working fluid is contaminated with ash or other residue such as flue exhaust gases [Schmidt], with wet "low quality" steam [Navajo], and for pulsatile blood pumping without causing damage to blood parts [Miller].

The arrangement of the boundary layer turbine is such that the surfaces are spaced to minimize the regions of laminar flow above the boundary layer. For steam, this spacing is approximately 0.04". For water, the ideal spacing is approximately 0.16". To get the most momentum transfer out of the fluid, we want to expose as much surface area as possible to as much of the fully formed boundary layer as possible. The disks can't be too close together so the boundary layers intersect, and we also don't want to leave too big of a gap or we'll be missing some of the high speed fluid that's rushing past. The exact spacing number depends on the input flow rate and the viscosity of the fluid.

From Turbine to Generator By Electromagnetic Induction

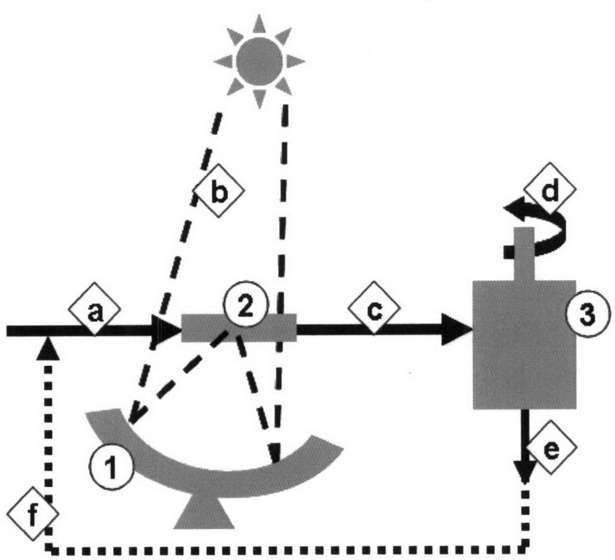
The turbine can be augmented with a small change to produce electricity directly. By placing magnets on the outermost disk of the rotor and coils on labyrinth plate of the stator, the turbine is also a generator.

When a conductor is placed in a changing magnetic field, an electrical current is induced in the conductor. This is known as electromagnetic induction and is described by Faraday's law of magnetic induction. In the case of a generator, it is common to geometrically condense a single long wire in a coil and move a magnet across the coils. The total voltage generated is the number of turns in the wire times the change in the magnetic flux through a single loop of wire.

Implementation

In this section I describe the entire system as well as experiments with various designs for the collector, boiler, and turbine.

The overall system is sketched in figure 1. Solar thermal energy is collected and concentrated to boil water into steam. The steam is fed into a turbine producing mechanical shaft-work. A complete working system to generate electricity from solar thermal energy has four parts, numbered in Figure 1 – (1) solar collector, (2) steam generator, (3) turbine, and (4) electrical generator (not shown in figure). The first three parts of the system were built to generate mechanical shaft work. The system decouples the mechanical to electrical conversion so users can pursue alternative mechanical means of energy storage such as pumping water into a tower or raising weights.



(a) Water is provided to the system at the inlet of the steam generator (2).

(b) The collector (1) focuses sunlight onto the steam generator (2) converting the water into wet steam

(c) Steam is directed to the turbine (3)

(d) Rotary shaft work is generated by the spinning turbine (3)

(e) Exhaust steam/liquid exits the turbine.

(f) Optionally, the exhaust liquid can be recycled into the feed water. The exhaust liquid is also purified and can be used as potable water.

Figure2: Overall solar thermal steam turbine system.

Integrated system

Figure 3: Integrated solar collector, boiler, and turbine. (Calero State Park, California)

Length of trough	6 ft
Width of trough	42 in
Reflector material	plastic coated metal film ("Space Blanket")
Boiler volume	1.78 gallons
Length of steam reheat piping	0 ft
Turbine rotor diameter	6.5 in
Turbine power rating @5000 RPM	0.2 HP

I coupled together a boiler, solar concentrator, and turbine. The sun's energy converted water to steam, and I ran a turbine off the steam. The turbine created rotational shaft work which can be coupled to nearly anything: water pump, compressor, fan, mixer, grain grinder, sewing machine, refrigeration compressor, and to power those few things that are truly electronic in nature, an electric generator.

The system above was assembled in 1.5 hours with help from another person. The most difficult part of the assembly was gluing the reflector material to the collector in a breezy field. Slotted design of the collector and focal point indicators cut directly into the collector allowed mounting the boiler without having to take careful measurements. The entire system was angled towards the sun and wedged into place with jack stands. When the collector was aimed properly at the sun, the dull black boiler surface easily showed the brightness of condensed sunlight.

Solar Collector

Figure 4: 180cm x 100cm Parabolic trough made from mirrored glass slats (Pabal, India)

Length of trough	180 cm
Width of trough	100 cm
Reflector material	mirrored glass

A 6' x 42" foot parabolic trough using a "space blanket" as the reflector built in California and a 180 cm x 100 cm parabolic trough using flat mirror slats made in India both obtained in excess of 270F at the focal line. In California, the trough needed to be repositioned approximately every 30 minutes to remain pointing at the sun. It boiled tap water in a boiler at the focal line within five minutes. In India, incoming monsoon winds consistently pushed large clouds in front of the sun, obscuring light to the reflector more than 75% of the time. When a small patch of sunlight appeared between clouds, the target at the focal line heated up to 280 °F immediately. However, there was not enough thermal mass in the target system to sustain the elevated temperature when the sun was obscured.

Collector Shape and Form

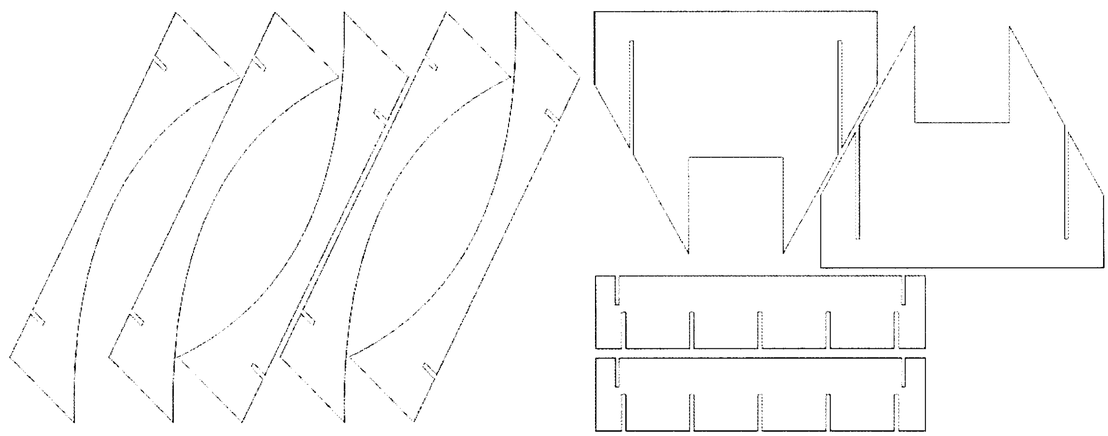


Figure 5: python-generated trough pieces laid out as a cut sheet in SVG format.

The solar collector is a parabolic form constructed using sheet metals and plywood. Historic collectors built in the field with arts-and-crafts processes have been shown to be highly efficient in heat concentrated. Computer calculated and controlled plotting increase the precision and efficiency of the collector. Additionally, precision plotting and cutting can allow "press-fit" assembly of the collector minimizing assembly time, installation errors, and cost of fasteners and specialty components.

A trough shape was constructed instead of a dish to avoid the complexity of tracking the sun in two axes. I tested trough-shaped collectors in California, Nevada, India, and South Africa and occasionally manually swung the collector to point at the sun. The trough design could be further customized to follow the arc of the sun given the latitude of installation and season of use. The boiler, described in the next section, would need to be curved to match the focal arc. A tracking circuit could be easily implemented using an Atmel AT Tiny 45 microcontroller which has an integrated temperature sensor. The AT Tiny 45 and associated driving components are a standard part of the distribution in the fab field labs [Fablab].

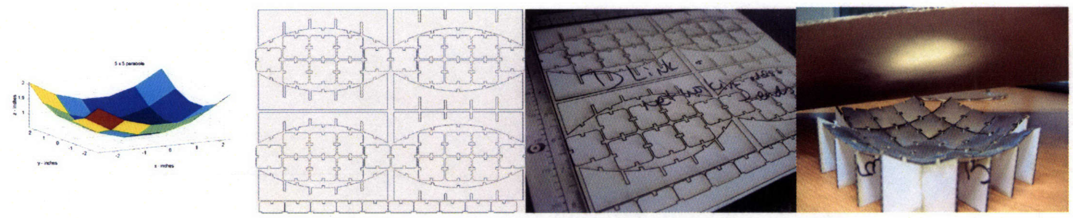


Figure 6: Slotted slide-assembly parabolic collector: software generated model, cut sheet, actual pieces, and assembled.

I also constructed parabolic dishes, although as mentioned above, they were abandoned for troughs for simpler pointing. In Ghana and South Africa, I tried x- and y-slicing a parabolic dish frame with slots for assembly as shown in illustration 5. (See appendix A for `parab.m`, the Matlab code to generate arbitrary sized frame slats). A limitation to the dish size was the maximum cutting width of the laser cutter (24"). Flat mirrored tile pieces or a continuous sheet of reflective material was placed over the frame and reflected light fairly well. In illustration 5, the focal area is approximately the area of a single tile. However, the frame required a lot of material, was laborious to cut for larger sizes than the desktop model shown, and unless attached with fasteners or adhesives, difficult to point. Much later in the process, an 4' x 8' NC router was added to the fabrication equipment at the field sites which would have made it possible to make larger frame pieces. The large router was used to make the trough ribs described above.

It was simple to modify the code from `parab.m` to `trough.m` (see appendix B) but by now I had moved on to Norway and India. In all of the field sites, the only licensed copy of Matlab was on my laptop so the code wasn't very useful for future work by locals. I rewrote the trough code in python, an interpreted, interactive, object-oriented programming language [Python] (see appendix C for `trough.py`). Python runs on nearly every machine platform and is freely usable and distributable, even for commercial use. Because Python uses modules, I could make use of a collaborator's implementation of toolpath file generation with just a single call [Scheffler].

The python script also automatically generates slotted end pieces and rails so that all pieces slide-fit into a complete support assembly. The front reflecting surface then has to be covered with a reflective material.

Reflector Material

Figure 7: Stapling aluminum flashing to shaping ribs to form parabolic reflector trough.

reflector material	purchase cost and quantity	$ / ft
regular aluminum foil	$1.99 for 12" x 25' roll	$0.08
space blanket	$3.99 for single 56" x 84" piece	$0.12
roofing flashing	$17.98 for 10" x 50' roll	$0.43

Table 3: Comparison of costs for reflector materials.

If I were only to consider reflectivity and cost, the best reflective material is aluminum foil, shiny side up [Harrison]. However, aluminum foil is delicate and difficult to work with over large surfaces. I found the overall best material was a surprisingly tough "Space Blanket" glued to a backing surface. My earliest attempts in South Africa at gluing aluminum foil to anything large resulted in big, smeared, wrinkly messes. In India, I set about sandwiching extra super heavy duty aluminum foil between two pieces of louver-type window pane glass. At the marketplace, I discovered that it was cheaper to buy mirrored glass than two pieces of comparably size regular glass[10]. This simplified the reflector construction as I could just the mirrored pieces directly. The mirrored slats were extremely fragile (perhaps two pieces of regular window glass would have been better) and their long lengths meant they were effectively long lever arms, increasing small forces at one end and breaking the glass at the supporting end pieces when high winds arrived.

In Nevada, I used 0.0086" thick rolled aluminum roofing flashing as the reflector material. Flashing is cold rolled which give both sides of the aluminum sheet a dull appearance.[11] Flashing was sufficiently thin to attach to the plywood shaping ribs with a regular-duty staple gun. While the Nevada trough focused sunlight adequately, a single sheet of moderately wrinkled aluminum foil placed on one end made a significant difference and led me to coating the California trough with a shiny surface. Aluminum foil is difficult to work with because it tears easily and it is impossible to prevent wrinkles (a newly purchased roll is often slightly wrinkled to begin with) so I tried a "Space Blanket". A space blanket is an extremely thin layer of aluminum (0.000256") bonded between two sheets of plastic. The lamination process preserves the shininess of the aluminum and the plastic allows for less gentle handling while still providing good sunlight reflection. A thicker material sold as "metallized mylar", available in large rolls four feet wide, was unsuitable as reflector material because the mirrored layer delaminated and turned milky and dull when humid, cold, or wet, and appeared to scatter light more than the space blanket. I used contact cement to adhere a single space blanket to the luan base of the trough.

[10] In a Pune glass shop, the price for a 5 in wide x 5 ft long were:
mirrored glass: 150 rupees
clear glass (need twice as many): 88 rupees
For reference, $1 USD = 46.42 INR at the time of writing.

[11] Aluminum foil is also cold rolled but has a shiny and dull side because two layers of aluminum are forced together through the roller press. The shiny side is where the foils are face to face and the dull sides are that which were against the rollers. The manufacturers of the most common aluminum foils roll two pieces of foil at the same time to approximately 0.00079" thickness each.

Fragility and Other Problems

Figure 8: One night's dirt accumulation on trough. (Pabal, India)

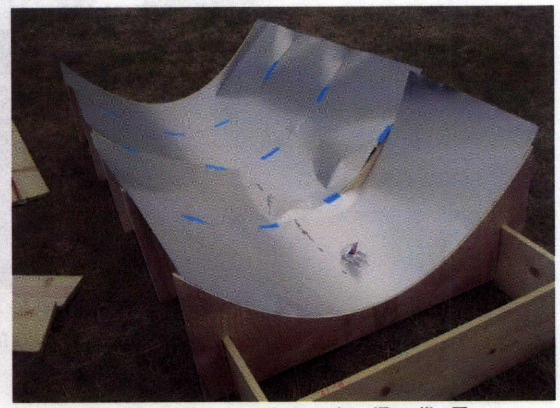


Figure 9: Wind damaged trough. (Devil's Tower, Wisconsin)

A recurring problem at every location was the cleanliness of the reflecting surface. Dirt and other accumulants on the reflector surface absorb rather than reflect and result in a less efficient collector. For long term setup and use, the reflectors need to be kept clean without requiring significant maintenance effort. This is significantly easier at some locations than others. The troughs were also basically an airfoil and were often damaged by wind. In India and Nevada, seasonally high winds preceding the monsoon season (India) and an incoming thunderstorm (Nevada) crumpled and torqued the thin reflecting surfaces into non-parabolic shapes.

Figure 10: Stiffening the reflective surface of the trough using thin plywood screwed into the shaping ribs. (Seven Troughs, Nevada)

The trough built in California used a 1/8" sheet of luan (thin plywood) screwed to the shaping ribs to stiffen the trough. Luan is a low grade plywood that comes in thin single-ply sheets and is usually stronger in one direction. While multiple ply plywood is manufactured with laminated layers of wood with grains aligned perpendicularly, luan is a single layer and is easily bent along the direction of the wood grain.

Building the solar trough led me to consider more generalized parametric generation of physical objects. The code examples provided, `parab.m`, `trough.m`, and `trough.py` could have front-ends written so that the user only inputs a solar intensity measurement and a desired volume flow of steam. The script should be able to sufficiently optimize on a full assembly design and generate an appropriate toolpath.

Steam Generator

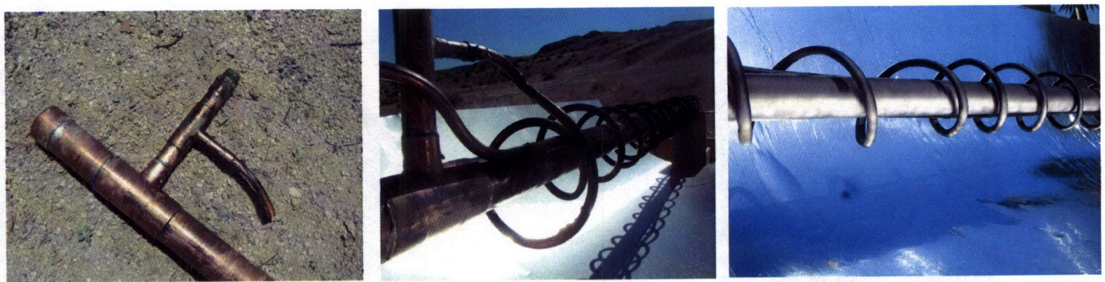


Figure 11: Steam generator made from 2.5" diameter copper pipe. Left showing fill and steam exit "T" in boiler. Center and right showing steam reheat coils.

Length of boiler	84 in
Diameter of boiler	2.5 in
Volume of boiler	1.78 gal
boiler material	copper

Precise parabolic concentrators focus heat to a small volume, forcing large amounts of heat energy into a small space. The intense heat at the collector's focus converts water to steam. The steam is reheated to dry it further.

A boiler was constructed using 2.5" diameter copper pipe sold for home plumbing. The ends of the copper pipe were sealed with caps held in place with regular solder. A reducing "T" was soldered into one end for both steam output and water filling. The entire boiler was painted flat black to improve heat absorption. The boiler was intended to hold a volume of water and run to completion, then refilled. The boiler was 84" long and held 1.78 gallons of water. 60 °F water from a garden hose was heated to boiling within a few minutes.

The steam output tubing was 3/8" inner diameter copper tubing (also used for household plumbing). I used a fairly large diameter tube because I did not want to restrict the flow rate of steam. In Nevada and California troughs, I coiled the output steam tubing around the water boiling pipe to allow the steam to heat above the boiling temperature of water and dry out further. It was very difficult to bend the 3/8" copper tubing into a coil that lay tightly against the surface of the 2.5" pipe, so there was a large gap between the coil and pipe. This meant that the coil was far from the collector focal line and

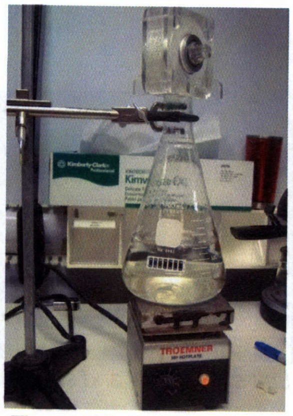


Figure 12: A flask of boiling water does not drive a turbine.

Figure 13: A well formed jet of steam from the pressure cooker boiler.

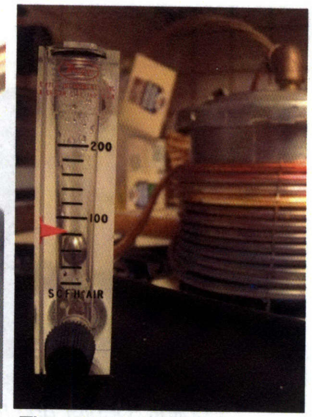


Figure 14: 60 SCFH volume flow from the pressure cooker boiler.

there would be no heat transfer between the turbine and pipe. The ambient air temperature was cool (77 °F in California) and a persistent breeze convectively carried away the heat from the thin tubing. The intended drying coil acted like a radiator and the steam recondensed into water in the coil, forming water plugs in the low parts of the coil. As the water in the boiler reached boiling and pushed steam into the tubing coil, splurts of hot water came out the exit end of the tubing. A better geometry for the drying tubing would have been to simply arrange the steam tubes longitudinally along the boiler pipe as close as possible and to fill the space with solder.

I was biased to a coil because of an earlier experiment with a pressure cooker. Initially, I simply coupled a small turbine to a flask of boiling water. Nothing happened except the turbine became wet with recondensed steam, because there was too little volume flow and too little pressure. Next I tried using the output of the steam jet on an espresso maker. Again, the steam recondensed too quickly and the turbine got wet. The steam jet on an expresso maker is intended to blow bubbles in milk and has high pressure but very little flow. So I turned to a larger pressure vessel, a kitchen pressure cooker one might use to cook rice or vegetables. I drilled out the pressure relief valve and replaced it with a 1/4" copper fitting and tube. I put the pressure cooker on my kitchen stove and turned the heat up to 260 °F. The output had greater flow, but still recondensed too quickly and the turbine slowly filled with water. The problem is that while steam can continue to absorb heat and build pressure, water is unable to hold heat above 212 °F and the water lay between the heat source and steam. I wrapped a long copper tube around the outside of the pressure cooker so that the heat would continue to heat the steam and dry it further. Finally I was making steam that didn't recondense. The steam produced 60 SCFH at 261°F through a 1/4" tube. It was time to make a larger volume boiler that could hold more water and still reheat the steam formed, as I describe at the beginning of this section.

Experimentation with flash conversion of small quantities of water into steam suggests it is a promising direction to pursue if the heat source is consistent. Using a column of water to maintain pressure on the feed side worked in the case of glass capillaries, but a large scale system would probably need a system with valves and seals.

Turbine

The turbine is the work engine and must be field producible. A boundary layer turbine was a promising design because it can be efficient at low operating pressures and is the very straightforward to construct. The design and construction of Tesla turbines employed 2-D (sheet) metals and plastics and used the least number as possible of pre-fabricated special parts such as springs, bearings, and fasteners.

Various industries have built boundary layer turbines for both shaft-work and electrical generation applications. Most turbines are large with 6" to 24" diameter disks and are generally hydro or wet-steam powered. Historical rotor efficiency has been reported to be 97%. Modern analysis of Tesla's design shows the rotor to be more than 95% efficient at fluid-to-rotary-motion transfer. The entire engine was 36% efficient overall with most of the losses found to be heat lost at the inlet and outlet [Rice].

Improved modern designs include improved seals and nozzles which can increase the overall efficiency. While a nozzle would have increased the turbine's efficiency, I wanted to make a direct comparison between input power and shaft work without having to account for a nozzle.

The 2 HP (1,491 watts) turbine is made from 9" diameter, 0.040" thick aluminum discs and 0.016" thick aluminum spacers. The first version used cheap steel bearings pressed into acrylic end plates. Acrylic end plates are more expensive than steel or other materials and was not strictly necessary but the clear transparent acrylic made it easier to observe the turbine in action.

The discs and spacers were cut on the waterjet cutter in stacks of 10 at a time, then deburred by hand. The acrylic housing was also cut on the waterjet cutter, although it was not necessary. An alternative process to waterjet cutting would have been to make a die and stamp from a harder metal then die-cut the spacers and discs. Die cutting would be more suitable if someone were to make several turbines of the same size. The underside of the cut would still need to be deburred by hand.

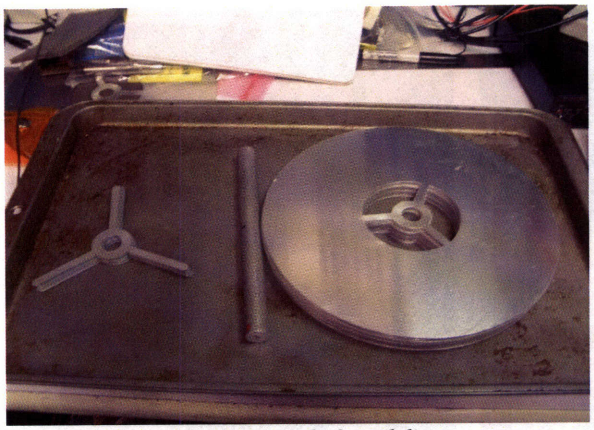


Figure 15: Aluminum spacers, shaft, and discs.

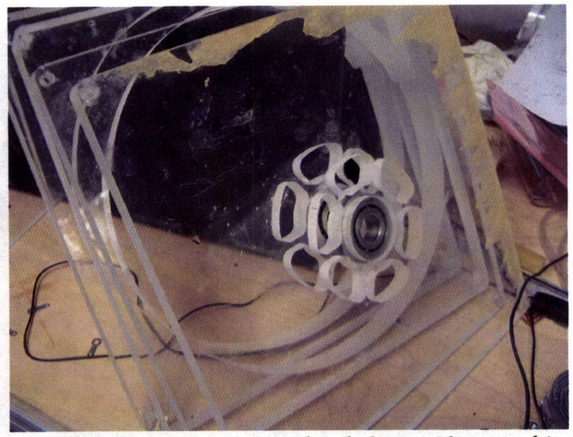


Figure 16: Acrylic housing and end plates with pressed-in steel bearings.

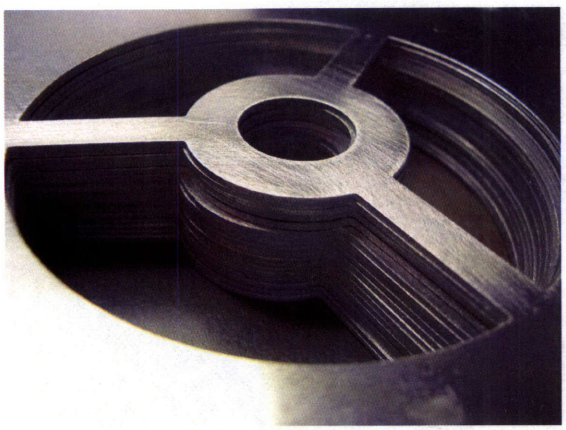


Figure 17: 0.040" thick aluminum discs.

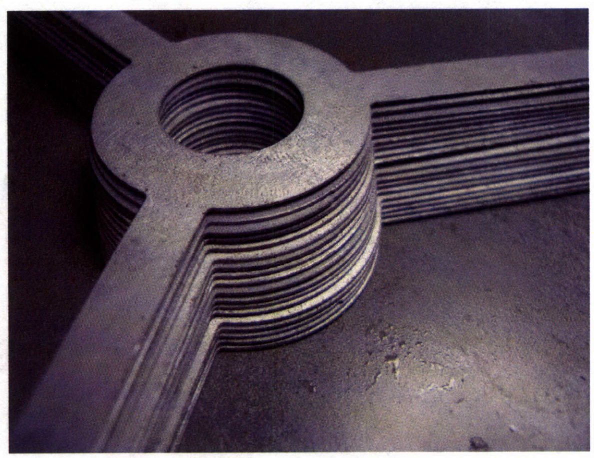


Figure 18: 0.016" thick aluminum spacers.

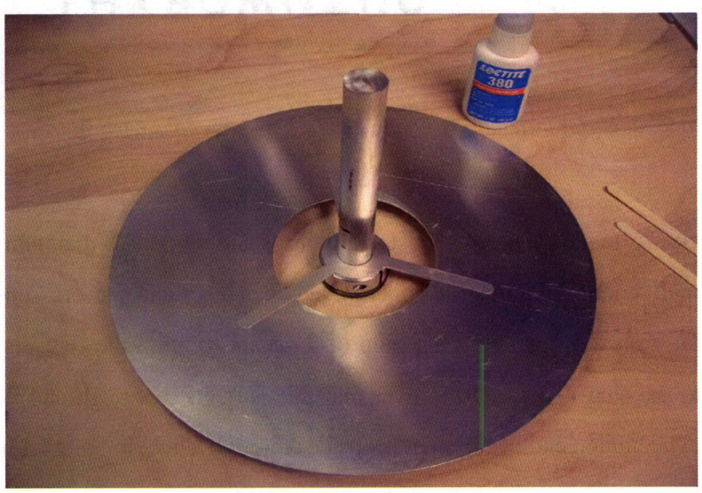


Figure 19: Assembling the disc pack onto the shaft

Figure 20: Cleaning the acrylic end plate prior to bonding

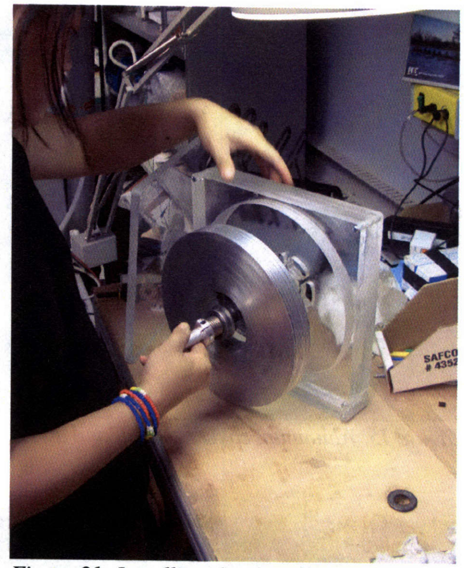


Figure 21: Installing the rotor into end plate and housing.

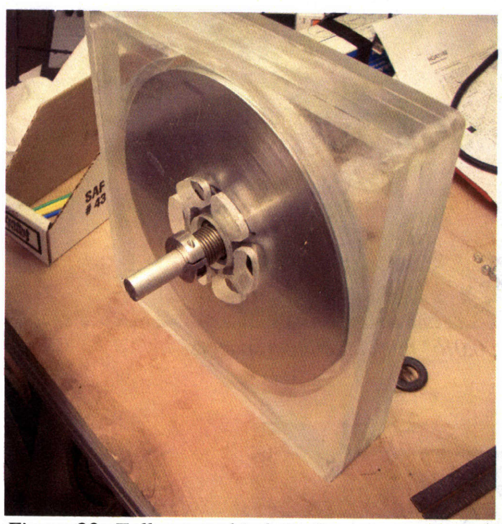


Figure 22: Fully assembled 9" diameter turbine.

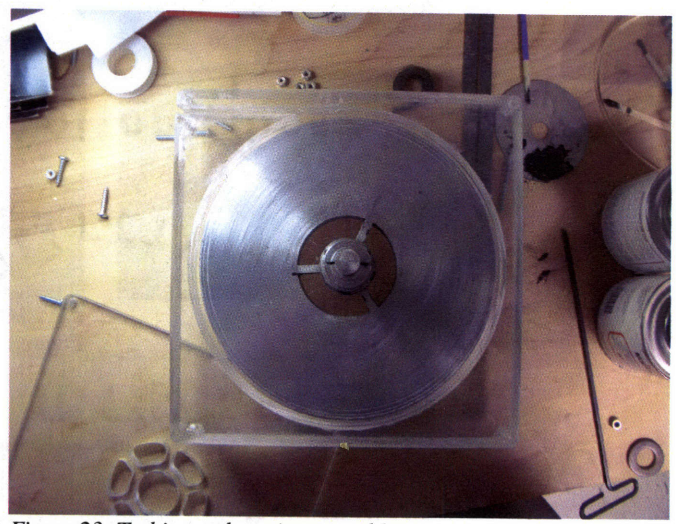


Figure 23: Turbine end cap is removable.

A rotor disc pack was made by alternately stacking discs and rotors. To maintain alignment of the vent port, I used a small amount of industrial adhesive between discs and spacers. I used a 3/4" shaft collar set perpendicularly on the shaft with the help of a square to align the first disc so that it would be perpendicular to the shaft. (Later I discover that this isn't good enough and this resulted in an off-balance rotor.) The hidden end of the shaft protrudes through a hole in the workbench.

The acrylic housing pieces was carefully cleaned with acetone then bonded together with acrylic cement. The rotor was loaded into the housing. One end piece needed to remain detachable in case I needed to take the assembly apart, so I used silicone sealant between it and the rest of the housing, then compressed the entire assembly with screws and nuts. A production, finished turbine probably wouldn't need to be taken apart and could be sealed with the acrylic cement as well.

Two greatest sources of momentum loss were friction due to bearings and imbalance of the rotor. The bearings posed the greatest source of frictional losses for the system and will require further research and experimentation to minimize their loss effects on the system. When I used a compliant centering flexure will constrain the bearings, the movement of the entire rotor would hit the housing and seals. In part, this is because the rotor was significantly off-perpendicular with the shaft.

Attaching thin rotor discs and spacers to the shaft so they were perpendicular to the shaft and rotationally aligned with respect to each other was more difficult than I expected. No simple jig held the shaft normal to the stacking surface and small tilt angles from each successive disc added up into a significant cumulative error noticeable when the rotor was spun. In one shaft design utilizing two flat and slotted parts press-fit into a 3-D part, I used long arms cut perpendicular to the axis of the shaft to guide the first disc expecting ensuing discs and spacers to lie parallel with the first disc. While the first disc was probably nicely perpendicular to the shaft, the entire 2.5" thick rotor stack was not. Much of this error is attributable to the burrs remaining on the discs and spacers leftover from the machining process. Another source of error are the non-uniformities and inflicted deformation of the sheet material used.

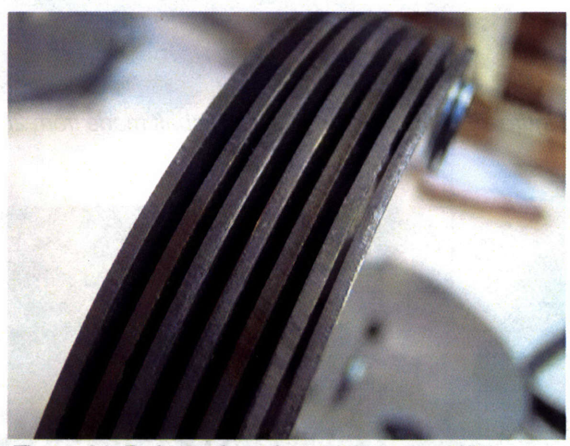


Figure 24: Deformation of a stainless steel disk, probably occurred during machining.

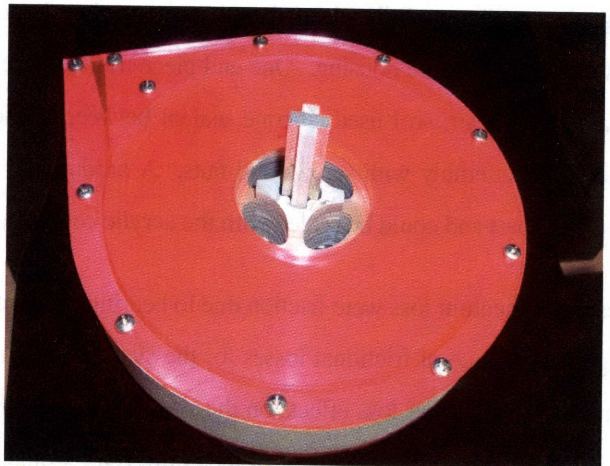


Figure 25: 6.5" diameter stainless steel disc turbine.

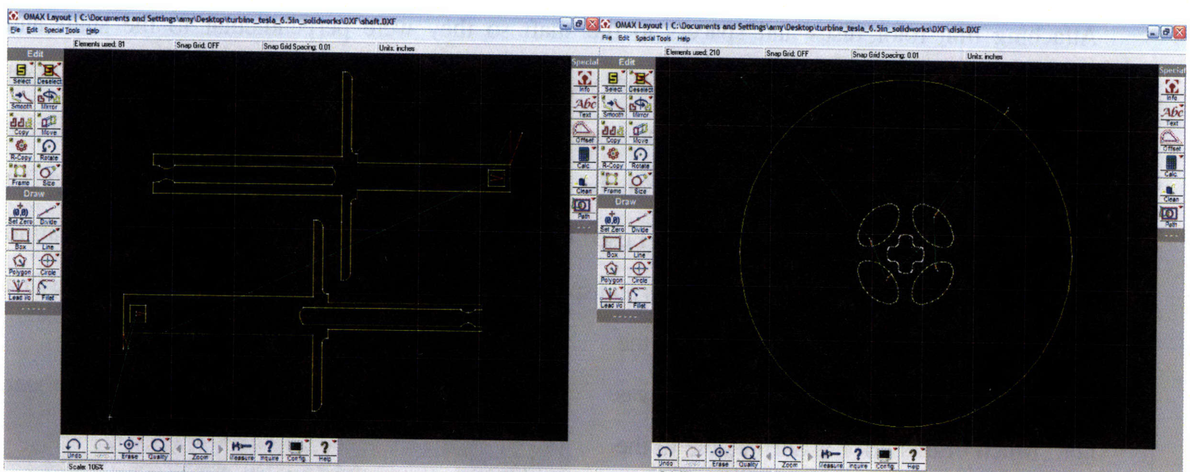


Figure 26: CAD drawing of slide-fit shaft made from 2D sheet

Figure 27: Plasma cut medium steel shaft. Plasma cutting was unable to give straight perpendicular cuts necessary for this design.

In the 9" diameter rotor turbine described above there are some special parts that I did not fabricate, they are the shaft, bearings, collars, and springs. (I don't count the bolts and nuts to hold the housing together because the housing could have been bonded but I use bolts so I can disassemble for inspection). To replace the aluminum bar used as a shaft, I cut two oppositely slotted parts that slide-fit and lock together. This shaft also included a flange meant to provide a perpendicular surface for the first disc to lie flat against during assembly.

The discs have a "plus"-shaped shaft hole to accommodate the assembled shaft profile. This conveniently helps the transfer of torque from disc to shaft. I attempted to cut this shaft from medium steel with an NC controlled plasma torch but the design relied heavily on the edges of the shaft to be cut perpendicularly and cleanly. Plasma is a vortex of swirling gas and cuts with a rounded, whirlly edge that would not allow the pieces to assemble correctly. The shaft used in the finished turbine was waterjet cut from 0.25" aluminum.

This turbine was meant to be run with live steam, so the the discs were cut from 0.060" stainless steel and spacers were 0.040" aluminum. The turbine has one thrust bearing on the underside and is meant to run in the horizontal position. The unassembled turbine parts travelled to South Africa and back before being assembled and the discs suffered some warping due to poor packaging. Once assembled, the rotor scraped against the end plates because it was very much off-perpendicular from the shaft. A thicker housing and pink acrylic end plates were hastily manufactured to allow more space for the rotor, and the entire turbine was shipped to California for integration with the solar trough boiler (results discussed in the *Evaluation* section).

The assembled 6.5" turbine has a theoretical power of 0.10 HP. The turbine was able to spin with solar thermal generated steam; in our tests with 17 SCFM @ 80 PSIG compressed air the turbine was able to spin the bicycle wheel described in the *Evaluation* section, but the values were too low for the power meter to record.

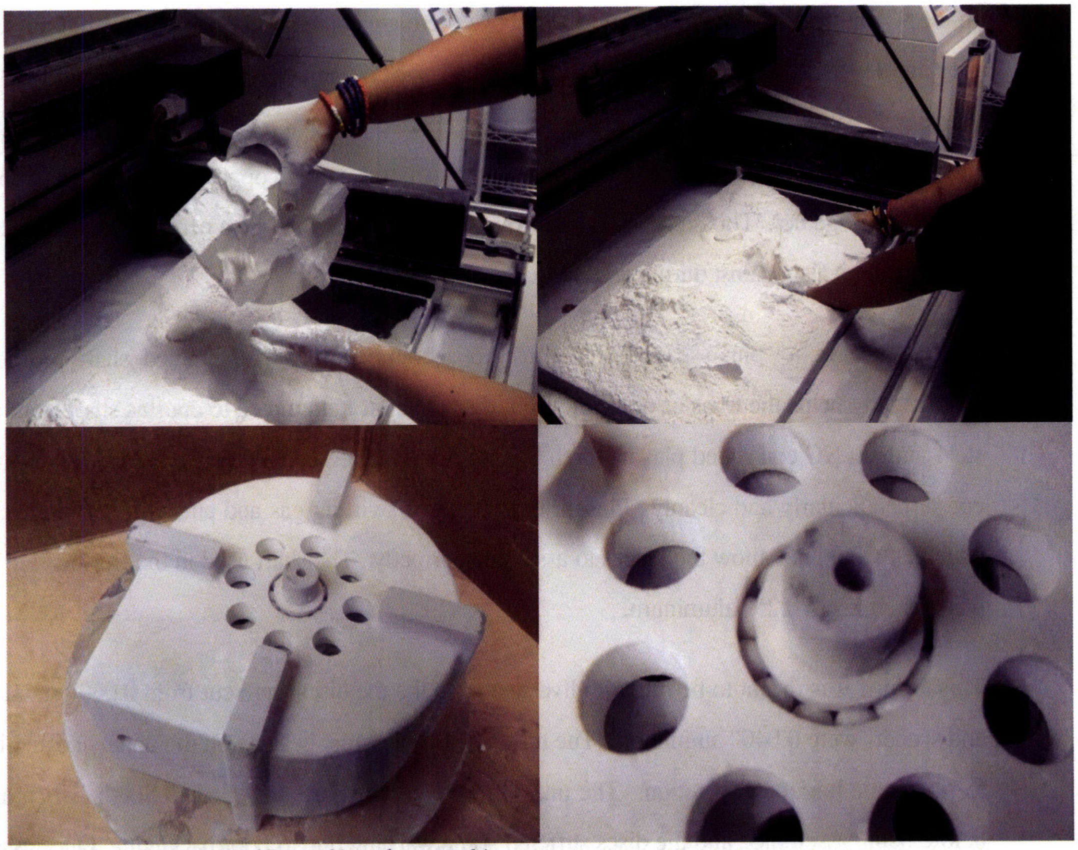


Figure 28: A direct-print, 3D, working plaster turbine.

Perhaps the most surprising of the turbine designs were the ones I didn't expect to work. Nearing the end of this research, we printed turbine designs on 3D printers[12]. One printer squirts microdroplets of binder into a loose plaster and the other printer melts and extrudes a plastic. In both cases, we allowed the printers to directly make the entire turbine completely assembled, even the balls captured in the bearings. In both cases, the print took a very long time and there was a fair amount of post-processing necessary to stabilize the working material and remove the support material. Also in both cases we varied the sizes of the digital design file arbitrarily, scaling the printed turbine for no better reason than being able to. And, as I indicated, although I completely did not expect it, these turbines *worked*.

[12] Again, I am indebted to Kenneth Cheung of the MIT SMArchS Computation Group, who printed these turbines despite my pessicism.

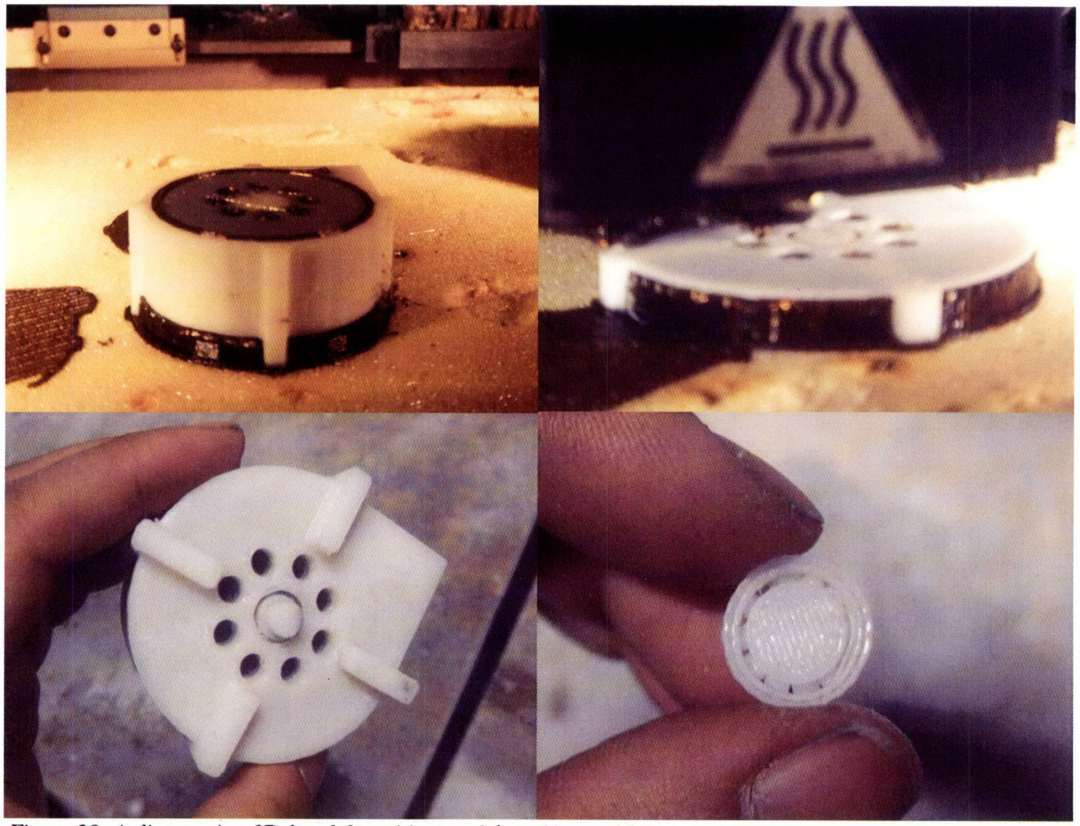


Figure 29: A direct-print, 3D fused deposition model working turbine.

The ability to print completely assembled, functional mechanisms coupled with an ability to mathematically describe devices is revolutionary. In a direct-print device, bearings are aligned and matched, rotor discs are perpendicular and symmetric (and therefore balanced), and the entire structure is completely assembled. Designing a mechanism without having to take into consideration it's assembly procedure and accesses alters the framework in which the designer is restricted. Function-based, mathematical descriptions of the system are solved just before the print-time and are portable, scalable, and easily customized. Function-based models don't have to be written so that the user describes just the physical parameters of the device but rather measurable parameters of the system environment. The compiler-solver can utilize a description module of known physical constraints (of the Universe) to find an optimal solution given the system environment and desired output.

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Evaluation

System Cost

	#	each	total	
SOLAR CONCENTRATOR				
3/4" plywood	2	$22	$44	
2" x 8" wood	3	$10	$30	
dry wall screws, box	1	$2.50	$3	
pint of contact cement	1	$5	$5	
space blanket	1	$4	$4	
			$86	**concentrator**
STEAM GENERATOR				
2.5" dia copper pipe	1	$20	$20	
2.5" end caps	2	$0	$1	
reducing T	1	$1	$1	
ball valve	1	$2	$2	
3/8" copper tubing	1	$16	$16	
2.5" dia mounting brackets	2	$0	$0	
solder, flux paste	1	$4	$4	
flat black spray paint	1	$2	$2	
insulating material	2	$2	$4	
			$50	**steam generator**
TURBINE (2HP)				
0.040" 12"x24" aluminum sheet	10	2.808	$28	Al sheet is $2.50/lbs, Al 6061 is 0.0975 lb/in^3
0.016" 12"x12" aluminum sheet	10	0.562	$6	
bearings	2	$4	$8	
0.25" 24"x26" aluminum sheet	1	52.65	$53	housing and shaft cut from this sheet
			$94	**turbine**
			$229	**TOTAL SYSTEM**

Efficiency compared to theoretical power of compressed air

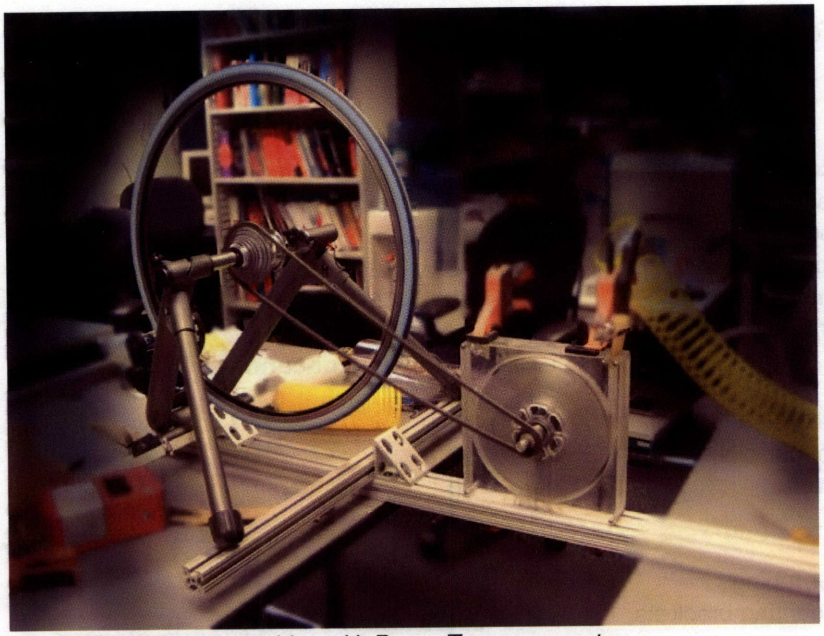

Figure 30: 9" diameter turbine with Power Tap power meter

I built a 9" diameter 3003 aluminum turbine with 19 discs and 0.016" disc spacing. The theoretical HP of this turbine is 2 HP or 1491 W at 6,000 RPM. Shop air available provided a maximum of 16 SCFM at 80 PSI. Load was applied to the turbine by coupling it via a chain to a bicycle wheel mounted on a cycling trainer which provides resistance to the wheel. The bicycle wheel had an integrated wireless power meter built into its hub which reported RPM and power in watts.

The turbine drove the system at a maximum 929 RPM and produced 21 W. The theoretical power of shop air delivered was 350 W, so the efficiency of our system is 6%.

The compressed air system was unable to provide enough flow to spin the turbine close to its designed operating point. It is possible that better efficiencies can be achieved with a turbine built to match the flow rate of the compressed air system.

The system did not employ a derailer to tension the chain because the additional load from the added tension prevented the turbine from starting (boundary layer turbines are difficult to start on input flow alone). I replaced the inexpensive, steel bearings with precision stainless steel bearings and the turbine went a little faster until it reached the resonance of the chain and the chain began to wildly bounce up and down, ultimately falling off the gears.

```
% eff.m
% calculate efficiency of turbine running on compressed air
% a. sun 8/01/06
%

%% MEASURE %%
degC = 20;
psi = 80;
scfm = 16;
W_t = 21    % measured turbine performance (watts)

% theoretical hp in compressed air
degF = (degC*1.8)+32;
cfm = scfm / ((520/(degF+460)) * (psi/14.7));
hp_ca = 0.2267 * cfm * ((((psi/14.7)+1)^0.283)-1);
W_ca = hp_ca * 745.70

% efficiency is out/in
percent_efficiency = W_t / W_ca * 100
```

Comparison to Photovoltaics (Solar Cells)

	very, very conservative	*expected average*	*ideal conditions*	*optimistic*
sunlight per day (hours)	6	8	12	12
solar irradiance per sq m (kW)	0.35	0.5	1	1
efficiency of system (%)	2.5%	5.0%	10.0%	20.0%
capital cost of system ($)	300	250	229	200
system lifetime (years)	0.75	2	3	5
capacity factor (%)	50%	75%	99%	99%
$ / kWh	**20.860**	**1.141**	**0.088**	**0.023**

Table 4: Cost per kWh of solar powered steam turbine. Capital cost of system does not include labor or manufacturing costs.

The calculation for cost per kW-hour is:

total collected kWh over device lifetime =
(sunlight hours / day)×(365.25 days / year)×(solar irradiance (kW)/ sq m)× (system life (years))×(2 sq meters)

useful kWh converted over device lifetime =
(total kWh over lifetime)×(efficiency of system)×(capacity factor)

cost per kWh =
capital cost of system ÷ useful kWh over lifetime

The wide difference between conservative and optimistic estimates of cost per kWh underscores the importance of understanding the input conditions at the deployment site. The "very, very conservative" case describes a location completely unsuitable for a solar powered economy (there sun is not very strong, the sunlit day is short, and weather conditions obscure the sun half the time) and the conversion device was built very poorly so that it converts only 2.5% of the little incoming energy to useful energy[13]. "Ideal conditions" describes a sunny, equatorial location where strong sunlight bathes the ground for long days. Clearly this is a more cost effective location for a solar thermal system.

[13] This is roughly analogous to Cambridge, Massachusetts, USA in the fall season.

Photovoltaic cells are increasingly recommended for deployment in rural places to generate electricity directly from solar photonic energy. Photovoltaic cells are made using semiconductor fabrication technologies and are usually assembled into large modules of cells connected to an inverter and power conditioner. Although significant improvements in efficiencies have been made, a fundamental limitation to solar cell efficiency is the narrow spectrum that cells respond to. Solar cells must be oriented so that incoming light is perpendicular to the surface so an accurate active pointing system must be used to make use of an entire day's sunlight.

Photovoltaic cells are made using semiconductor fabrication processes with high temperatures and toxic chemicals. The cells cannot be made "locally", so consumers are dependent on manufacturers. In recent years, the cost of photovoltaic cells have decreased based on market proliferation and economies of scale.

A successful energy producing device must produce affordable energy. Affordability must consider the entire system's costs from obtaining feed source to waste processing. The differences between photovoltaic products and our device are most obvious when one considers manufacturing and acquisition costs. Photovoltaics cost approximately $6000 per kW to manufacture not including the initial acquisition cost of the silicon fabrication facility. Over a predicted 20 year lifetime, photovoltaics costs $0.37 per kWh in a sunny location [Solarbuzz]. The device described in this research costs $153 per kW to manufacture and has a lifetime of 2 years. Our device costs $0.08 per kWh (using the ideal conditions in table 15)[14].

[14] Photovoltaic output is in electrical kWh where this system is in mechanical kWh.

Impact

It will take at least a decade before we find out how fab labs empower individuals and change communities. We know for certain that the fab labs are an alternative learning model and we cannot do wrong by offering different paths to supplement learners' curriculum. How those people affect the communities around them remains to be seen, but there is potential for great, sweeping changes.

Large and complex problems require lots of people and resources. We often assume these projects require a centralized structure, a singular program manager who directs managers who direct workers. To solve the world's biggest problems we can instead take a distributed approach by enabling ordinary people to collaborate. The open intellectual network of the fab lab is extremely important and allows work at one location to feed into work at another. Viral dissemination of knowledge and peer-to-peer, grassroots learning allows individuals to take advantage of each other, creating a much larger impact as a whole.

My diary doesn't go far enough back to record Bashir's[15] age precisely. He was probably 10 years old when I met him in dusty, rural Western India in the winter of 2002. Bashir wanted to conquer what he saw as oppression over rural farmers – the energy load and water-sharing outages that perpetuated a frustrating inability to industrialize. Bashir demanded to be taught about windmills, generators, water pumps, control circuitry, water sensors, dams, and wanted to access that information via the computer we were to leave behind. We performed experiments as we could; the fab lab equipment list was infantile then and consisted only of the 2.5D mini-mill and knife cutter. It was Bashir's precocious enthusiasm for changing the landscape of the rural Indian farmer that dragged me away from a proper engineering job and into the field. When I left, I gifted Bashir with every technical book I'd brought with me but wondered what he could make of that limited, static resource.

At the time, the best we could do to connect Bashir to the outside world was a painfully slow dial-up connection which hinged on the up-and-down rural phone and power system. Later,

[15] Not his real name

when other fab labs around the world shared a deep desire to connect, it spawned a global collaborative project to create antennas that could be made with the resources in every fab lab. A solution for the fab lab connectivity problem came from within the fab lab and has since spread into a commercial business for at least one community.

Kalomi[16] was 8 years old in 2004 when she became an international movie star. Heads of state, generals, corporate presidents around the world have watched her make a circuit board in the Takoradi fab lab in Ghana. After hanging around the lab and watching older boys learning about circuits for a little while, Kalomi needed very little help to make and build her circuit. The reasons Kalomi was able to make her first circuit are the fab inventions that lower the entry threshold for new and beginning users. She might have quickly lost interest with a cumbersome process that requires an unreasonable amount of hand-holding from an experienced user. Kalomi didn't need to know circuit analysis to fabricate the physical board and she didn't need to understand the entire circuit to learn how to her modifications to the circuit affected its behavior. She skipped straight to the fun part of making the board, then learned about circuit parts and microcontrollers as needed along the way. The opportunities Kalomi has for sharing and continuing to learn about circuits grow as the network of other fab lab peer learners grow, increasing in a viral fashion.

Through play in the fab lab, Kalomi has had exposure to scientific concepts and experienced technical experimental processes. Now Kalomi is 10 years old and smarter than all the kids her age (and several of the much older kids) and something of a frustration for her teachers. Her parents have written us ask if we could help find a place to educate her because there is not an advanced schooling option in Takoradi. I imagine that for a 10 year old child, it must seem a punishment to be torn away from a loving family simply because one is smart.

[16] Not her real name

Future Work

Solar Collector

The collector could be optimized in two ways. First, the python program could take as input the latitude of site of intended use and plot an optimal shape that requires the least amount of sun tracking. Second, a simple tracking circuit could be built using standard deployed fab lab components and a motor. The trough shape is convenient in that it only requires tracking the sun in one axis. At the moment, the motor to swing the trough must be purchased but there has been some development work in the field labs to make motors [Fab]. The motor is a device which transforms electrical power to mechanical work, but there is opportunity instead to consider a passive, thermal-pneumatic system for sun tracking [Zomeworks]. Several other details require optimization at the user site, such as the method of adhering the reflective material to the surface and the thicknesses of materials used for the support structure.

Steam Generator

Modifications to the boiler present the most significant impact on efficiencies for the least amount of effort. Immediate benefits will be seen by applying a proper coat of black paint, creating a steam reheating system thermally connected to the water chamber, and installing a wind block to prevent convective cooling of the steam. The boiler must also be modified to continually fill with water. For rural, drought plagued rural locations, a closed cycle steam capture and condensation stage after the turbine is necessary.

Turbine

The measured efficiency of the turbine system does not adequately represent the achievable efficiency. My error was in not matching the input flow available to turbine parameters so the 2 HP turbine was run far from it's ideal operating point and as a result, appeared significantly less efficient. I plan on constructing another compressed air turbine to create plots of torque at various loads. I will need to find either a source of greater air volume to match the sensitivity of ranges for the power meter or find or devise a power meter which can operate at lower ranges (below 0.5 HP).

It was much more difficult than expected to assemble the rotor so that it was balanced and the disc pack is perpendicular to the shaft. Direct 3D printing the turbine solves this problem, but in the meantime any assembled device must be more carefully trued. I could not simply rely on the parallelness of stock material and a decent hand-deburring process. One can assume that while this can be improved, it will never be completely balanced. Allowing the rotor to dynamically stabilize once spinning seems like a desireable solution but the geometry of the housing will need to be designed so it can take into account the space that the rotor will sweep through.

The rolling element bearings I employed are a sore point because the rest of the turbine can be made on site whereas to replicate the rolling element bearings used one must turn to high quality, hardened steel which is unreasonable to expect to find and machine in remote locations. A very promising alternative are fluid bearings, also known as hydrostatic bearings. Fluid bearings that use air as the lubricant require a consistent 0.0005" (12.7 micron) gap between the moving and static elements. As with the Tesla boundary layer turbine, the air bearing is not a new idea, early work in air bearings date back to 1897 [Devitt] but exceeded the machining precision, metallurgy, and computational capabilities of the time. Today, field fab lab machining capabilities have sub-micron precision [Modela] and ever-faster processors available for design optimization to prevent rotor oscillation. One of the most difficult challenges remaining in utilizing an air bearing will be the design that allows for easy assembly of the final device.

General improvements to the turbine design include seals to prevent inlet flow from flowing "around" the rotor to the vent ports and a redesign of the housing section to minimize Nozzles and additional inlets would make the turbine more efficient. A nozzle shape is best computationally derived to optimize geometry with flow conditions.

An immediate modification to the printed turbine design is to add wells to glue in magnets and spools about which to wind wire so that the printed device needs only these two post-processing steps to become a generator or motor.

Direct 3D Printing

The limiting factors for direct-printing useful devices are the engineering materials available and the print time. Additionally, an open source design and modelling package must be integrated with machine command. At present, there are no field-deployable 3D printing machines in the field but nascent work in contour crafting [Khoshnevis] and micro-scale digital assembly [Popescu] suggest we're just around the corner.

Functional representation of physical things

When I set about designing these turbines, I used the time-honored and tedious engineering process of designing and entering every minute detail in CAD. I iterated in guessing at reasonable input parameters, solving a double surface integral to determine the disc diameter, number of discs, disc spacing, and other physical parameters, guessing at a range of reasonable bearing sizes, finding that the bearing size is unavailable, and cycling through the guess-calculate-design process. Finally, when physical parameters and part availability converged, I sketched the turbine parts by hand on paper, then drew each part in Solid Works before finally creating drawing files. Those drawing files were then brought into a tool path generator CAM package which generates the machine code to drive the actual machining step.

One of the biggest benefits of a mathematical representation of physical devices is that it leads to a digital description that can be treated modularly. Physical devices can be represented as functions in a description language that defines the object along with it's material properties and logical relationships with other objects. These functions would reveal to the user measurable parameters (such as solar irradiation) and hide non-measurable engineering state functions (such as entropy) within the model. Lower level parameters in the models are the physical variables that can be accessible to the user only when higher level system or environmental parameters don't fully constrain the final product. A functional representation modeling community associated with the fab labs is taking the first steps towards being able to functionalize real objects, reducing real things to functional programs. Another related effort is defining ".fab", the language for machine compilable physical object description. In the future I will write code that describes the behavior, not physical parameters, of a device and I will be able to use a library of modules that describe likely solution classes and system constraints. See appendix E for an example of a functionally described bearing.

Conclusions

There is a revolution about to come as regular people all over the world gain access to digital fabrication that will enable them to build complex products such as solar energy conversion devices. I've shown that it is possible to build multiple versions of successful solar energy collectors and steam turbines in field fabrication sites.

Collectors of various designs were employed in India, America, and South Africa and consistently provided in excess of 270 F thermal heat for input to the boiler. Steam generators varied in size and shape but generally took only a few minutes to convert tap water (approximately 55 deg F) to steam. Several boundary layer turbines were constructed in different processes from acrylic, ABS plastic, plaster, paper, aluminum (3003, 7075, and 6061 alloys), and stainless steel and operated with compressed air, funneled wind, water, and steam. The turbines ranged in sizes from 3" diameter rotors to 9" diameter rotors; the most common size were 6" or 6.5" diameter for convenience and access to raw materials. Somewhat surprisingly, *all* turbines worked including the plaster turbine bound with cyanoacrylate. The 9" diameter, 2 HP air turbine was measured to be 6% efficient fully loaded (at stall).

The process of creating an entire solar thermal system for making useful energy using fabrication available in the field required many iterations from the initial design. Commercial fabrication machines for "desktop" use (as opposed to specialized lab facilities) are emerging onto the consumer market for individual users to plug into their home computers and will soon be as common as printers. Using these early products, the fab labs place in the field a tight cycle among design, fabrication, and field testing to allow people to experimentally converge on an ideal design. Understanding the engineering principles behind the mechanisms isn't strictly necessary for a person to begin development and those concepts can be discovered as needed. This model of learning has a much lower barrier of entry than traditional Western models. Technologies *development*, not just end-user technology products, have become accessible to persons not formally trained in sciences or engineering.

My argument for building a boundary layer turbine for field implementation is that the savings from making a more manufacturable, less complex device provides a sort of credit towards the overall turbine efficiency and power output levels. The amount energy necessary to create a boundary layer turbine is significantly less than what is needed to make a photovoltaic cell or Stirling cycle engine. An inefficient solar collector is better than no solar collector at all; there is a minimum threshold that must be correct for the system to simply work. Over time, efficiency gains can be experimentally and incrementally implemented while the user enjoys a non-zero energy source.

Boundary layer turbines were interesting because of their ease of manufacturability, but in the course of research we realized that what really needed is a fundamental shift in manufacturing from subtractive to additive processes. Materials sets for additive fabrication are immature and will require development before we can "direct print" robust, working products. Nonetheless, I was able to "direct-print" working turbines using existing machines. The limited number of proof-of-concept turbines made with the 3D plaster printer (Z-Corp) and plastic resin deposition printer (Stratsys) surprised everyone by actually working right out of the printer. The printed turbines were a conventional design that takes into account features needed to assemble many separate parts. But these printed turbines emerged with all parts integrated – so bearing balls were grown inside bearing races, and turbine discs, spacers, and shaft (and bearing inner hub) were created as a solid integral unit. Field fabricated turbines tuned to the locations they are intended to serve will both drive and be driven by the expanding engineering material set available to the additive machines that will be used to make the turbines. The most pressing needs are for stiffer and more robust structural materials as well as those with electrical and magnetic properties.

While the continued development of solar energy conversion devices are not dependent on fabrication machines still under research, the need for energy in rural places is part of the co-evolving "fab" story around the world. In addressing one of greatest technical challenges shared globally among rural and underdeveloped places, I've demonstrated that commercial "desktop" machining products can enable regular people in rural places to apply technology towards solving critical needs.

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Appendix A: parab.m

```
% parab.m
% parabola mesh
% the final product is xslices_x, xslices_z, yslices_x, yslices_z
%
% A. Sun 2005
%
% © Massachusetts Institute of Technology 2005
% Permission granted for experimental and personal use;
% license for commercial use available from MIT.
%

clear all;

grid=6;
offset=.5;   %base thickness inches
focus=6;        %inches
diameter=9;     %inches
w_plate=.1;  %plate thickness inches   --  unused
w_nub=.103;    %nub width inches
h_nub=.103;    %nub height inches
w_grid=.113; %width of grid plates inches

N=grid;

A=1 / (4 * focus);

x=(-diameter/2):diameter/N:(diameter/2);
y=(-diameter/2):diameter/N:(diameter/2);

for n=1:N+1,
    y_p(n)=A * y(n)^2+offset;

    for m=1:N+1,
        z(m,n)=A * x(m)^2+y_p(n);
    end
end

%% take a look at the product
figure(1); clf reset;
surf(x,y,z);
axis equal;

figure(2); clf reset;
for n=1:N+1,
    subplot(N+1,1,n)
    plot(y,z(n,:));
end

%I'll do nubs that raise up from the parab surface
```

```
z_x=[];
for m=1:length(z),
    x_slice = [];
    z_slice = [];
   for n=1:length(z)-1,
         middle=(y(n)+y(1+n))/2;
         thisnub(1)=middle-(w_nub/2);
         thisnub(2)=middle-(w_nub/2);
         thisnub(3)=middle+(w_nub/2);
         thisnub(4)=middle+(w_nub/2);
         z_thisnub(1)=A * thisnub(1)^2+y_p(m);
         z_thisnub(2)=z_thisnub(1) + h_nub;
         z_thisnub(3)=A * thisnub(3)^2+y_p(m)+h_nub;
         z_thisnub(4)=z_thisnub(3) - h_nub;
         x_slice = [x_slice x(n) thisnub];
         z_slice = [z_slice z(m,n) z_thisnub];
   end
   x_slice = [x_slice x(length(x))];
   z_slice = [z_slice z(m,length(x))];

  z_x=cat(1,z_x,z_slice);
end

%% view output
figure(4); clf reset;
for n=1:N+1,
   subplot(N+1,1,n)
   plot(x_slice,z_x(n,:),'bx-');
   hold on;
   plot(x, z(n,:), 'ro-');
   axis equal;
   axis([-diameter/2, diameter/2, 0, focus*2]);
end

%% x and y slices are the same except for the
%  slots to fit them together.  arbitrarily,
%  let x have slots on top and y slots from the bottom
z_y = z_x;

% y is easy because it doesn't have to be inserted
base_y_z = [];
for d = 1:length(y),
   base_y_z_slice = [0];
   for r = length(y)-1 : -1 : 2,
     base_y_z_slice =[  base_y_z_slice 0 z(d,r)/2 z(d,r)/2 0 ];
   end
   base_y_z_slice = [ base_y_z_slice 0 z(d,1) ];
   base_y_z = cat(1, base_y_z, base_y_z_slice);
end

base_y_y =[ ];
base_y_y = [ y(length(y)) ];
for i=length(y)-1:-1:2,
```

```
  base_y_y = [ base_y_y y(i)+w_grid/2 y(i)+w_grid/2 y(i)-w_grid/2 y(i)-
w_grid/2 ];
end
base_y_y = [base_y_y y(1) y(1)];

% finished y slices have base appended
yslices_y = cat(2,x_slice,base_y_y);
yslices_z = cat(2,z_y,base_y_z);

figure (5);
plot(yslices_y,yslices_z(1,:));
axis([(-grid/2)-1,(grid/2)+1, -1, (focus*4)+2]);
axis equal;
title('y slice #1');

% x base is easy because it doesn't have any notches,
% but need to modify the top of it for notches

base_x_x=[ x(length(x)) x(1) x(1)];
base_x_z=[];
for d=1:length(x),
  base_x_z_slice=[0 0 z(d,1)];
  base_x_z = cat(1, base_x_z, base_x_z_slice);
end

notches_x_x = x_slice(1:5);
for i=6:5:length(x_slice)-1,
  notches_x_x = [notches_x_x  x_slice(i)-w_grid/2 x_slice(i)-w_grid/2
x_slice(i)+w_grid/2 x_slice(i)+w_grid/2];
  notches_x_x = [notches_x_x  x_slice(i+1:i+4)];
end
notches_x_x = [notches_x_x  x_slice(length(x_slice))];

notches_x_z = [];
for n=1:N+1,
  notches_x_z_slice = z_x(n,1:5);

  for i=6:8:length(notches_x_x)-1,
    % these four are downgoing grid slots
    notches_x_z_slice = [ notches_x_z_slice A*notches_x_x(i)^2+y_p(n)];
    notches_x_z_slice = [ notches_x_z_slice (A*notches_x_x(i+1)^2+y_p(n))/2];
    notches_x_z_slice = [ notches_x_z_slice (A*notches_x_x(i+2)^2+y_p(n))/2];
    notches_x_z_slice = [ notches_x_z_slice A*notches_x_x(i+3)^2+y_p(n)];

    % these four are upgoing nubs
    notches_x_z_slice = [ notches_x_z_slice A*notches_x_x(i+4)^2+y_p(n)];
    notches_x_z_slice = [ notches_x_z_slice A*notches_x_x(i+5)^2+y_p(n)+h_nub];
    notches_x_z_slice = [ notches_x_z_slice A*notches_x_x(i+6)^2+y_p(n)+h_nub];
    notches_x_z_slice = [ notches_x_z_slice A*notches_x_x(i+7)^2+y_p(n)];
  end

  notches_x_z_slice = [notches_x_z_slice
A*notches_x_x(length(notches_x_x))^2+y_p(n)];
  notches_x_z = cat(1, notches_x_z, notches_x_z_slice);
end
```

```
xslices_x= cat(2,notches_x_x,base_x_x);
xslices_z= cat(2,notches_x_z,base_x_z);

figure (6);
plot(xslices_x,xslices_z(1,:));
axis([(-grid/2)-1,(grid/2)+1, -1, (focus*4)+2]);
axis equal;
title('x slice');

%% write outputs as svg file
% find min, max x and y
xmin=-diameter-1;
xmax=diameter+1;
ymin=-diameter-1;
ymax=diameter+1;

fp = fopen('parab.svg','w');

fprintf(fp,'<?xml version="1.0" encoding="UTF-8"?>\n');
fprintf(fp,'<!DOCTYPE svg PUBLIC "-//W3C//DTD SVG 1.0//EN"
"http://www.w3#.org/TR/2001/REC-SVG-20010904/DTD/svg10.dtd">\n')'
fprintf(fp,'<svg width="%fin" height="%fin" viewBox="%f %f %f %f">\n',xmax-
xmin,ymax-ymin,xmin,ymin,xmax-xmin,ymax-ymin);
fprintf(fp,'<g style="stroke:rgb(0,0,0);fill:none">\n');

% the two ends don't cross with anything, so leave out
for s=2:N,
   fprintf(fp,'<polyline points="');
   for p=1:length(xslices_x),
      fprintf(fp,'%f,%f ',xslices_x(p),xslices_z(s,p))
   end
   fprintf(fp,'" style="fill:none"/>\n');
end

for s=2:N,
   fprintf(fp,'<polyline points="');
   for p=1:length(yslices_y),
      fprintf(fp,'%f,%f ',yslices_y(p)+diameter+1,yslices_z(s,p))
   end
   fprintf(fp,'" style="fill:none"/>\n');
end

fprintf(fp,'</g>\n');
fprintf(fp,'</svg>\n');

fclose(fp);
```

Appendix B: trough.m

```
% trough.m
% parabolic trough
% the final product is one copy of identical ends to hold slats
%
% A. Sun 2006
%
% © Massachusetts Institute of Technology 2005
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% license for commercial use available from MIT.
%
clear all;

N = 100; % number of points
trough_width = 42;  % inches
base_height = 4;    % inches
focus = 8;          % inches
cutout_margin = 3;  % inches
cutout_width = 1;   % inches
cutout_height = 8;  % inches

x=(-trough_width/2):trough_width/N:(trough_width/2);

for n=1:N+1,
    z(n)=(1 / (4 * focus)) * x(n)^2+base_height;
end

base_x = [ 0 cutout_margin cutout_margin cutout_margin+cutout_width
cutout_margin+cutout_width trough_width-(cutout_margin+cutout_width)
trough_width-(cutout_margin+cutout_width) trough_width-cutout_margin
trough_width-cutout_margin trough_width ];
base_z = [ 0 0 cutout_height cutout_height 0 0 cutout_height cutout_height
0 0 ];

base_x_rev=[0];
for i=1:length(base_x),
    base_x_rev(i) = base_x(length(base_x)-i+1);
    base_z_rev(i) = base_z(length(base_z)-i+1);
end

path_x = [ 0 x+trough_width/2 base_x_rev ];
path_z = [ 0 z base_z_rev ];

figure(1); clf reset; hold on;
plot(path_x, path_z);
plot(trough_width/2,focus+z(round(length(z)/2)),'o');
axis equal;

%% write outputs as svg file
% find min, max x and y
```

```
xmin=0;
xmax=max(path_x);
ymin=0;
ymax=max(path_z);

fp = fopen('trough.svg','w');

fprintf(fp,'<?xml version="1.0" encoding="UTF-8"?>\n');
fprintf(fp,'<!DOCTYPE svg PUBLIC "-//W3C//DTD SVG 1.0//EN"
"http://www.w3#.org/TR/2001/REC-SVG-20010904/DTD/svg10.dtd">\n')'
fprintf(fp,'<svg width="%fin" height="%fin" viewBox="%f %f %f %f">\n',xmax-
xmin,ymax-ymin,xmin,ymin,xmax-xmin,ymax-ymin);
fprintf(fp,'<g style="stroke:rgb(0,0,0);fill:none">\n');

fprintf(fp,'<polyline points="');
for p=1:length(path_x),
    fprintf(fp,'%f,%f ',path_x(p),path_z(p))
end
fprintf(fp,'" style="fill:none"/>\n');

fprintf(fp,'</g>\n');
fprintf(fp,'</svg>\n');

fclose(fp);
```

Appendix C: trough.py

```
#!/usr/bin/env python
#
# trough.py
# parabolic trough
# the final product is one copy of identical ends to hold slats
#
# A. Sun 2006
#
# © Massachusetts Institute of Technology 2005
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# license for commercial use available from MIT.
#

from __future__ import division
from toolpath import *

## orientation: x = width, y = length, z = height
# t = trough    h = height
# b = base      l = length
# f = frame     w = width
# n = notch     m = margin

## physical parameters  (inches, everything in inches)
material_thickness = 0.151     # inches
num_ribs = 5;  # number of rib slots to put in the rails

tw = 12;    # trough width (inches)
bh = 1;     # base height (inches)
tl = 12;    # trough length (inches)
focus = 4;  # inches

boiler_radius = 0; # radius of boiler that rests on the stand end (inches)

## derived physical parameters
nw = material_thickness;   # notch width (inches)
nm = 0.1*tw;   # notch margin (inches)
nh = ((1/(4*focus)*((tw/2)-(nm+nw))**2)+bh)/2 # notch height (inches)
evaluate parabola at nm+nw and divide by 2
fh = nh*2;   # frame_height (inches)
frame_overhang = tl*0.2;    # overhang on each end

## internal
N = 100;    # number of points to evaluate parabola

## rib (make num_ribs)
#
x = []
z = []
for n in range(N+1):
    x.append((tw/N)*n-tw/2);
    z.append((1 / (4 * focus)) * x[n]**2+bh)
    x[n]+=tw/2
```

```
b_x = [ 0, nm, nm, nm+nw, nm+nw, tw-(nm+nw), tw-(nm+nw), tw-nm, tw-nm, tw ]
b_z = [ 0, 0, nh, nh, 0, 0, nh, nh, 0, 0 ]

b_x.reverse()

path_x = [ 0 ] + x + b_x
path_z = [ 0 ] + z + b_z

writesvg('rib', path_x, path_z)

## frame - rail (make two)
#
fl = frame_overhang*2 + tl  # exact trough length is between insides of
ends
railb_x = [ 0, ((fl-tl)/2)-nw, ((fl-tl)/2)-nw, (fl-tl)/2, (fl-tl)/2, fl-
((fl-tl)/2), fl-((fl-tl)/2), fl-((fl-tl)/2)+nw, fl-((fl-tl)/2)+nw, fl ]
railb_z = [ fh, fh, nh, nh, fh, fh, nh, nh, fh, fh ]
ribspace = (tl - 2*nw) / (num_ribs-1)
railt_x = [ 0 ]
railt_z = [ 0 ]
for n in range(num_ribs-1):
    railt_x = railt_x + [ n*ribspace+frame_overhang+nw,
n*ribspace+frame_overhang+nw, n*ribspace+frame_overhang+nw+nw,
n*ribspace+frame_overhang+nw+nw ]
    railt_z = railt_z + [ 0, nh, nh, 0 ]

railt_x = railt_x + [ fl-(frame_overhang+nw+nw), fl-(frame_overhang+nw+nw),
fl-(frame_overhang+nw), fl-(frame_overhang+nw), fl ]
railt_z = railt_z + [ 0, nh, nh, 0, 0]
railb_x.reverse()
railb_z.reverse()
rail_x = railt_x + railb_x
rail_z = railt_z + railb_z

writesvg('rail', rail_x, rail_z)

## frame - end (make two)
#
# yunknown = ((xunknown - xa)*yb - (xunknown-xb)*ya)/(xb-xa)
# the two known points are (0 , fh) and ( (tw/2)-boiler_radius , focus+bh)
xa = 0
ya = fh
xb = (tw/2) - boiler_radius
yb = focus + bh
end_top_x = [ 0, 0, nm, nm, nm+nw, nm+nw, (tw/2)-boiler_radius ]
end_top_z = [ 0, fh, (((nm-xa)*yb)-((nm-xb)*ya))/(xb-xa), nh, nh, (((nm+nw-
xa)*yb)-((nm+nw-xb)*ya))/(xb-xa), focus+bh ]

# for now just make a square notch
end_top_x = end_top_x + [ (tw/2 - boiler_radius), tw/2 + boiler_radius ]
end_top_z = end_top_z + [ focus+bh-boiler_radius, focus+bh-boiler_radius ]

# the two known points are ( (tw/2)+boiler_radius , focus+bh) and (tw , fh)
xa = (tw/2) + boiler_radius
```

```
ya = focus + bh
xb = tw
yb = fh
end_top_x = end_top_x + [ (tw/2)+boiler_radius, tw-nm-nw, tw-nm-nw, tw-nm,
tw-nm, tw ]
end_top_z = end_top_z + [ focus+bh, (((tw-nm-nw-xa)*yb)-((tw-nm-nw-
xb)*ya))/(xb-xa), nh, nh, (((tw-nm-xa)*yb)-((tw-nm-xb)*ya))/(xb-xa), fh ]

end_x = end_top_x + [ tw, 0 ]
end_z = end_top_z + [ 0, 0 ]

writesvg('end', end_x, end_z)
```

Appendix D: bearing.hf

"Hyperfun Project is a free software development project for functionally based shape modeling, visualization, and animation. The project is based on a so-called function representation of geometric objects and supporting software tools built around the HyperFun language." http://www.hyperfun.org

The compiled and polygonized output of the following code creates an .stl file which can be fed directly into a 3D printer (ie, Z-corp or Stratasys FDM) or "sliced" for stacked 2.5-D machining.

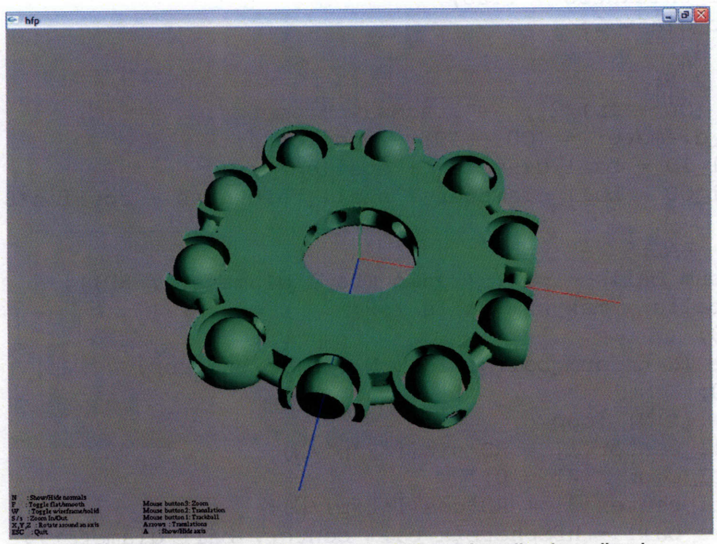

Figure 31: Rendering of a polygonized functionally described bearing.

```
-- bearing.hf
-- caged bearing
--
-- A. Sun 2006
--
-- (c) Massachusetts Institute of Technology 2005
-- Permission granted for experimental and personal use;
-- license for commercial use available from MIT.
--
bearing(x[3], a[1]){
   -- DEF --
   array origin[3], xt[3];
   array ball_center[3];  -- ball center
   pi = 3.14;
   epsilon = 0.015;   -- resolution limit of deposition machine

   -- ORIENTATION --
   -- [x,y,z] = [width, height, length]
   origin = [0, 0, 0];

   shell_thickness = .125;
   shaft_dia = 1;
   OD = 3;
   ID = 2.5;
   RD = (OD + ID)/2 ;  -- raceway diameter
   ball_diameter = (OD - ID) - epsilon*4;
   shell_ID = ball_diameter + epsilon*4;
   shell_OD = ball_diameter + shell_thickness + epsilon*8;

   -- -- BALLS -- --
   max_num_balls = pi / ( asin (ball_diameter / RD));
   num_balls = max_num_balls / 2;
   N = 0;
   while (N <= num_balls) loop N = N+1; endloop;
   i = 0;
   while (i<N) loop
     ball_center[1] = RD*sin(i*2*pi/N);
     ball_center[2] = 0;
     ball_center[3] = RD*cos(i*2*pi/N);
     this_ball = hfSphere(x,ball_center, ball_diameter);
     this_envelope = hfSphere(x,ball_center,shell_ID);
     this_shell = hfSphere(x,ball_center,shell_OD);
     if (i=0) then
       balls = this_ball;
       envelopes = this_envelope;
       shell = this_shell;
     else
       balls = balls | this_ball;
       envelopes = envelopes | this_envelope;
       shell = shell | this_shell;
     endif;
     i=i+1;
   endloop;
```

```
    -- -- INNER HUB -- --
    hub_OD = hfCylinderY(x,origin,ID);
    hub_ID = hfCylinderY(x,origin,shaft_dia);
    h = x[2];
    h_hi = 0.6*ball_diameter+h;
    h_lo = 0.6*ball_diameter-h;
    hub = h_hi & h_lo & hub_OD \ hub_ID ;

    -- -- CAGE -- --
    cage_ring=hfTorusY(x,origin, RD, ball_diameter/3);
    cage_chain= cage_ring & hub | shell \ envelopes ;
    y = x[2];
    y_hi = 0.667*ball_diameter+y;
    y_lo = 0.667*ball_diameter-y;
    cage_O = hfCylinderY(x,origin,OD-0.05*ball_diameter);
    cage_I = hfCylinderY(x,origin,OD-1*ball_diameter);
    cage = y_hi & y_lo & cage_chain & ( cage_O \ cage_I );


    ---- COMPLETE MODEL ----
    bearing = cage | balls ;
}
```

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