MotorPrinter

www.bestelectricmachine.com

Project Title:

MotorPrinter: Only 3D Printer of Electric Motors or Generators

Bottom Line Up Front (BLUF):

In keeping with the spirit of "*Innovating for Our Clean and Sustainable Energy Future,*" the MotorPrinter Project goes where no project has gone before:

> "Creatively fabricate the only 3D-Printer that rapidly manufactures virtually any category of the efficient axial-flux (AF) form of electric motor and generator (i.e., electric machine) to democratize and encourage the research, development, production, and application of axial-flux electric machines (AF-EM) for electric vehicles (EV)."

Story Behind The MotorPrinter Project

During technical conversations with professional attendees while presenting at several academic research and development venues, such as the Sensor-less Control For Electrical Drives (SLED) 2012, the Electric Ship Technologies Symposium (ESTS) 2013, the International Electric Machines and Drives Conference & Expo (IEMDC) 2013, and the IEEE Electrification and Transportation Conference (IETC) 2014, suggested that the few specialty AF-EM manufacturers closely guard their proprietary AF-EM manufacturing technology solely for the commercialization of their brand of AF-EM and as a result, custom AF-EM prototyping for academic research and development is unique, costly and time consuming. All agreed that a 3D Printer[1] for enabling the rapid manufacture of any category of AF-EM(s), including the unique ability to manufacture with high performance magnetic core materials, such as amorphous ribbon, would democratize and encourage the research, development, production, and application of AF-EM(s) for at least electric vehicles (EV).

The Big Picture of The MotorPrinter

1. Electricity is the most convenient and efficient means of distributing energy, particularly energy converted from renewable fuels, such as wind, hydro, solar, etc. Electricity distribution is expected to double in the next two decades but already 20% of energy converted from *all* fuels is distributed by electricity. With industrial electric motors and generators (i.e., electric machines) consuming 60% of all electricity generated and generating nearly all electricity consumed, any applied efficiency

[1] http://en.wikipedia.org/wiki/3D_printing

improvement to electric machines would improve the overall efficiency of the entire electricity infrastructure.

2. The electric motor-generator drivetrain of the fully electric or hybrid vehicle (EV) is considered the most convenient means for improving the overall efficiency of the transportation sector, which is the largest consumer of energy. In testimony, sales for hybrid EVs increased from 136,000 in 2011 to 440,000 in 2012, which equates to at least 440,000 large integral horsepower electric motors (i.e., > 15KW) manufactured for EV in 2012 alone. With present trends suggesting EVs will rapidly proliferate over the short term, any applied or enabling efficiency improvement of electric machines would improve the overall efficiency of the entire transportation infrastructure.

Most would agree that any efficiency improvement of the electric motor and generator (i.e., electric machine or **EM**) would dramatically reduce our total energy and carbon footprint but more importantly, a practical manufacturing means that cost-effectively enables the efficiency improvement is fundamental to its successful introduction and application.

Needs Solved By The MotorPrinter

1. Virtually all electric motors or generators (i.e., electric machines) are magnetic rotating electric machines with three possible form-factors, the so-called radial-flux (RF) electric machine (RF-EM), the axial-flux (AF) electric machine (AF-EM), and the transverse-flux electric machine (TF-EM). Unlike the RF-EM with the traditional cylinder (rotor) inside a cylinder (stator) arrangement (that we are all familiar with) and the AF-EM with the more unusual side-by-side rotor and stator disk arrangement that are already used in some EV(s), the very rare Transverse Flux Machine (TFEM) is notoriously difficult and expensive to manufacture for practical EV application. Although the first electric machine built by Faraday, himself, was an AF-EM, the RF-EM has been universally adopted because of the limits of AF-EM manufacturing technology since the beginning of electric machines. Ironically, theoretical considerations by Polard[2] show the AF-EM reduces copper utilization by 13-14% and reduces iron utilization by 21.5-32.5% compared to a similarly rated RF-EM but with over a century of manufacturing tooling investment and trust in the RF-EM, AF-EM manufacturing or tooling is non-existent, proprietary, or custom. As a result, the creative research, development, or commercial application of the AF-EM is comparatively non-existent except in small specialty markets where the performance virtues of the AF-EM are cost-effectively applied, such as the EV market.

2. A Design News article by senior technical editor, Ms. Ann Thryft, states, "*Oak Ridge National Laboratories (ORNL) is getting into 3D printing in a major way…[by]*

[2] Zahra Nasiri-Gheidari, Hamid Lesani,"A Survey on Axial Flux Induction Motors," PRZEGLAD ELEKTROTECHNICZNY (Electrical Review), ISSN 0033-2097, R.88 NR 2/2012.

develop[ing] technology that will 3D print an entire production model car."[3] For good reason, today's rage is 3D Printing for rapid product prototyping or for production of custom solid shapes by additively fusing thin layers of plastic or metal materials to progressively take the form of the shape with little waste by altering the properties of the plastic or metal materials from solid to liquid and back to solid during application. So even the best state-of-art 3D Printer is *not suitable for manufacturing the magnetic steel core of electric machines*, which always requires at least the additive stacking of thin insulated laminations of specially "pre-processed" steel ribbon (i.e., electrical steel) with special but delicate electromagnetic properties that cannot be altered during the manufacturing process. Although the ORNL 3D Printer may one day manufacture the entire conventional vehicle including the internal combustion engine and drivetrain as suggested, the ORNL 3D Printer cannot manufacture the entire electric or hybrid vehicle (EV) of the future, which includes an electric machine, without MotorPrinter.

3. The conventional laminated electrical steel core of any electric motor or generator (i.e., electric machine) shares 15% of the total energy loss of the electric machine. By simply using better performing magnetic core materials, such as readily available amorphous metal ribbon, core loss could be reduced by a staggering 80% over conventional electrical steel laminations with a proportional reduction in adverse byproducts, such as greenhouse gas. But the same enhancing properties that make the magnetic core material electromagnetically efficient also make the material too difficult to manufacture into an electric machine core without damaging the electromagnetic performance properties of the material. Since high performance core materials have been available for decades, it is not the availability of high performance core materials but instead, it is the lack of a practical *enabling means* to cost-effectively manufacture electric machines with high performance core materials.[4]

The MotorPrinter Solution

1. During the research and development of Synchro-Sym electric machine system technology (SS-EMS), MotorPrinter was conceived and patented as a vertically enabling manufacturing tool of SS-EMS technology; but conveniently, MotorPrinter will similarly manufacture any category of AF-EM, such as internal and surface PM electric machines, induction electric machines, and reluctance electric machines.

2. MotorPrinter, is the only 3D Printer that completely builds a precision AF-EM core from raw magnetic metal ribbon with customizable slot shapes and channels, which are the place-holders for electric machine windings, permanent magnets, or saliencies, and with a precision flat air-gap surface without secondary operations; but also, MotorPrinter directly builds the integral frame with bearing assembly from raw

[3] Ann R. Thryft, Senior Technical Editor, Materials & Assembly, Design News, "3D-Printing an Entire Car & a Bigger, Faster Commercial 3D Printer," 3/14/2014
[4] http://web.ornl.gov/info/reports/1983/3445605663010.pdf

low cost structural materials instead of assembling the traditional inventory of precision castings. MotorPrinter has virtually no tooling consumables and shows a significant reduction of cutting waste compared to traditional manufacturing methods of electric machines. MotorPrinter is a cost-effective, self-contained, environmental friendly, non-smokestack, household power, hybrid 3D Printer with a small footprint that fits inside a standard shipping container for self-contained portability, such as an academic institution installation, but is capable of building several hundred horsepower rated AF-EM(s). The MotorPrinter's method of cutting versatile shapes into single layers of preprocessed electrical steel ribbon (e.g., amorphous ribbon) was already empirically shown by experimental cooperation with several fiber laser cutter companies to successfully mitigate the structural deformation and damaging effects of heat stress on the delicate properties of high performance core materials, such as amorphous (and nano-crystalline) metals, that in the past, have continually prevented their introduction into electric machines.

3. Although MotorPrinter can prototype AF-EM with high performance material, such as amorphous metal, it would have limited purpose without a scalable manufacturing means for high volume production. The production speed of MotorPrinter is mostly dependent on the cutting placement speed, power, and cost of the Fiber Laser Cutter with high power fiber laser cutting speed of over 500 inches/sec empirically demonstrated, which reasonably calculates to an annual production rate of many thousands of AF-EM within the same small MotorPrinter footprint of a standard shipping container or MotorPrinter POD.

4. The portable footprint and low electrical power requirements of MotorPrinter will allow MotorPrinter to be moved to immediate facilities, such as academia's parking lot, to accommodate customers' secure research and development or instead, the customer can remotely download over the internet (clowd electric machine manufacturing) their set of predefined specification, such as slot form, for just-in-time remote manufacturing.

The MotorPrinter Functional Operation

As shown in the rudimentary concept drawing of Figure 1, the MotorPrinter concept of operation is straight forward. Two rotary tables provide the "supply bobbin" and the "finish spooler." As the spool of raw amorphous ribbon is unwrapped from the supply bobbin, the ribbon passes through the commercial fiber laser cutter (FLC) with XY positioning that at least performs the customized slot cut as programmed into the self-contain computer-aided-design (CAD) package of the turn-key FLC, and then the finished ribbon is wrapped onto the finish spooler. Not shown is the EM bearing assembly, which is first placed on the finish spooler before wrapping begins to form the ribbon wrapping spindle and becomes an integral part of the frame and bearing assembly of the finished core when wrapping completes. Only the annulus of the raw bearing assembly requires slight precision finishing for bearing mounting. The progressive wrapping of the cut or finished ribbon onto the finish spooler eventually forms the toroid or disk core of an AF-EM. Each fiber laser slot cut is initiated by sensing the predefined

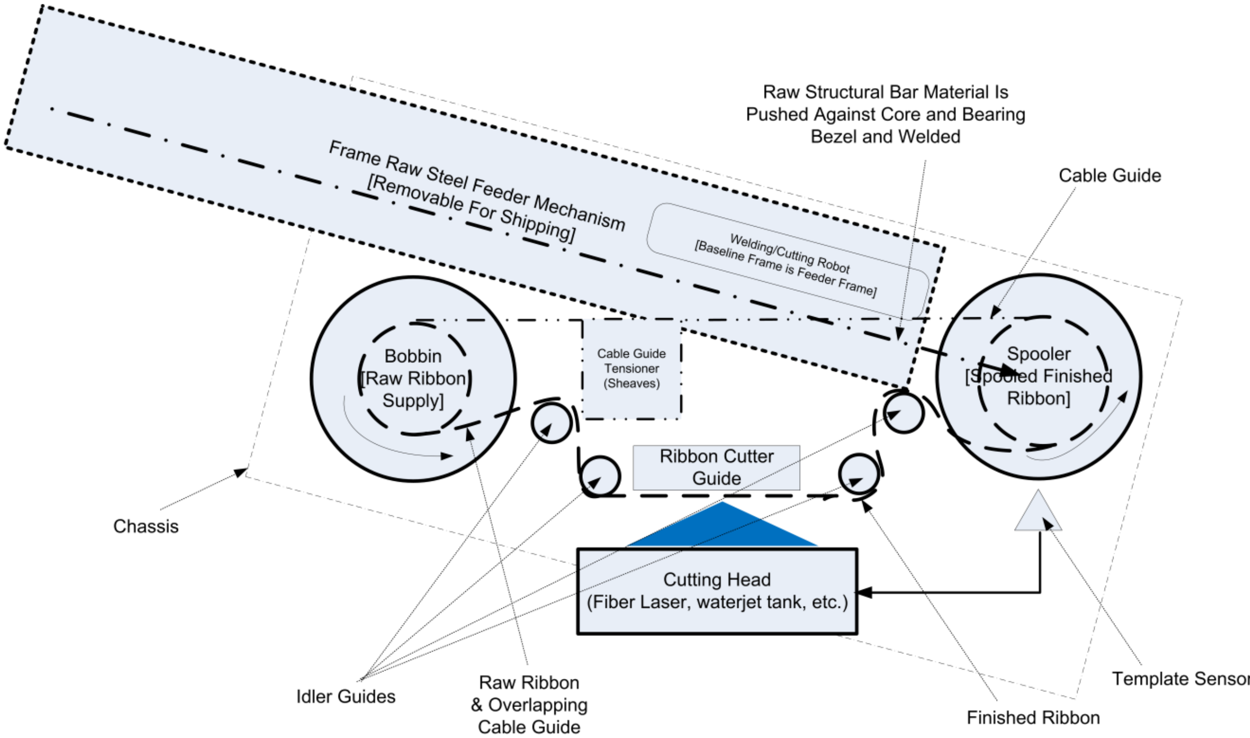

Figure 1

map of slot channels provided by a slot template, which is a “predetermined map” of slot positions that synchronously follows the rotation of the finish spooler, and as a result, the slots always precisely aligned over the previous wrapped layer of slots regardless of the unpredictable diameter of the wrapping because of the varying thickness of the raw ribbon. The slot template can be software, such as a predefined lookup table of stepper motor steps to the next slot, or hardware, such as opaque lines on a cardboard disk that are optically detected, all of which avoids the inaccuracies of dynamically calculating the position of the next slot cut from the speed of rotation and the unpredictable diameter of wrap layers. A “cable guide” surrounds the entire path of the ribbon from the supply bobbin to the finish spooler to guide the moving ribbon within the expected path. On each wrap, the ribbon is forced against the flat surface of the finish spooler by at least the cable guide to assume the precision flatness of the finish spooler, which is the air-gap side of the finished toroid core. After the wrapping is completed, the robotics of the “raw steel feeder mechanism” with a rudimentary concept shown in Figure 2 precisely places bar or channel stock (for instance) onto the back-side of the finished toroid core like spokes on a bicycle wheel with the “Welding/Cutting robot” attaching the bar or channel stock to the back-side of the toroid core with the guide cable continually holding the finish toroid in alignment to the finish spooler, which also acts as a precision alignment jig for at least the precision flat air-gap surface and frame assembly. Any imprecision of the ribbon and frame materials is neutralized by the forgiveness of welding.

A rudimentary concept of the “raw steel feeder mechanism” is shown in Figure 2. The entire MotorPrinter may be tilted for feeding the raw frame stock to the feeder slide by gravity. The bar stock slides over the rotary table by the propulsion of the roller stepper until it bumps up to the bearing assembly (not shown). After the up/dwn control moves the bar stock against the spooled toroid core, the welding/cutting robot holds, cuts and then welds the bar stock to the toroid core and bearing assembly. The process is repeated until the all bar stock spokes are welded to the toroid core and bearing assembly for a finished toroid core with integral frame and bearing assembly.

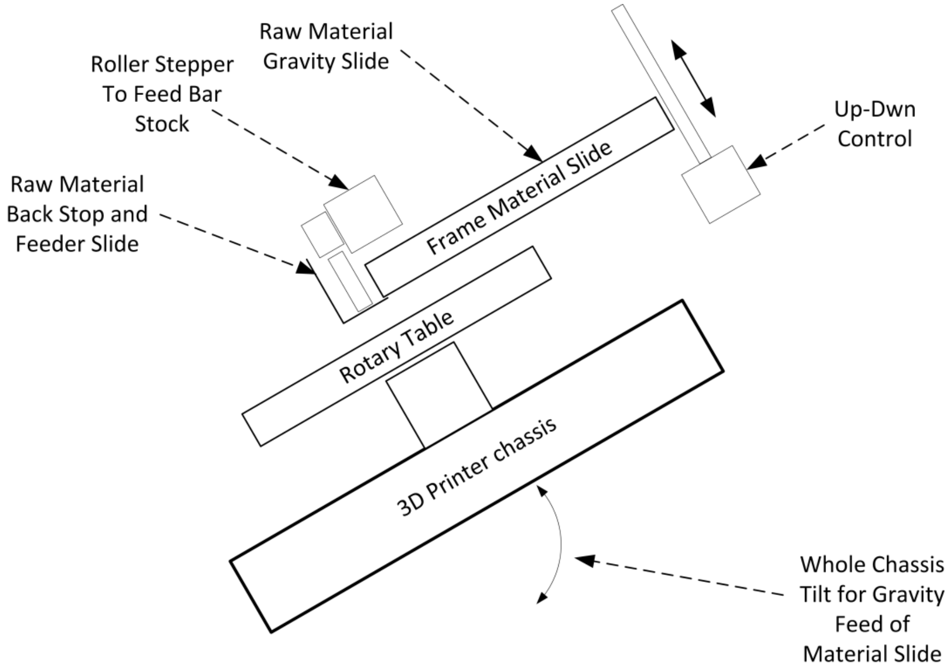

Figure 2

Different from other Laminated Object Manufacturing 3D Printers, MotorPrinter comprises at least three unique intellectually claimed aspects: 1) the slot template means for initiating the remote slot cutting on a single wrap layer to relieve heat stress on the material while precisely aligning the slots on the toroid without dynamic calculations; 2) the air-gap side of the ribbon progressively assumes the precision flat surface of the finish spooler on each wrap; and 3) the cable guide for actively guiding the ribbon path.

The MotorPrinter Project Work Breakdown Statement (WBS)

Without considering: 1) the simple concept description; 2) the issued patent vetting; 3) the empirical study in cooperation with fiber laser cutter manufacturers; and 4) the concept vetting with major amorphous material manufacturers, MotorPrinter is a simple creative fabrication project. There are familiar examples of creative fabrication projects with comparable straight-forward simplicity to the MotorPrinter project, such as the creative custom motorcycle fabrication projects of Orange County Cycles or Jesse James Cycles reality TV series. Likewise, the MotorPrinter's creative fabrication project will leverage readily available commercial components into the design to significantly reduce non-recurring engineering (NRE), costs and schedule risks, such as components from hardware stores, hobby shops, auto parts stores, off-the-shelf laser cutting systems with self-contained turn-key XY positioning and a computer-aided-design (CAD) package, etc.

Similar to any creative fabrication of a custom motorcycle (e.g., Orange County Cycles) and with the design flexibility built into a “creative fabrication project” to save development cost and schedule, there may be significant difference between the rudimentary concept of Figure 1 and the final MotorPrinter.

The Integrated Master Plan and Schedule

Master Plan	Master Schedule
Formalize the system design specification (SDS) from the presently archived concept design information, the bill of materials, etc.	4 wks
Labtop/Acquisition/Control (Arduino linux) platform (HW assembly and SW programming)	Start on week 4
As is customary, chosen Fiber Laser Cutting (FLC) company prepares the FLC equipment to meet minor customer specification, such as cutting slots during ribbon movement.	Start on week 4
Produce the ad hoc layout and assembly drawing (LAD) with chassis dimensions from the SDS.	4 wks
Purchase all commercially available components with best case delivery and cost based on the SDS and LAD, such as structural steel stock, controllers, etc., and purchase the only custom components, such as precision rotary tables, but less fiber laser cutter. Perhaps modify SDS/LAD to meet availability of components. [Lead time for commercially available parts is short.]	Start on week 8
Fabricated chassis using a rotary laser guide for precision alignment.	2 wks
Fabricate/Assemble the delivered rotary tables with bearing assemblies, variable speed motor, and mount in alignment with chassis	2 wks
Fabricate/Assemble Cable guide	2 wks
Fabricate/Assemble Framer Robot	2 wks
Validation: Developmental testing and calibration; optimize fiber laser cutting for best & fastest cut.	2 wks
Verification: Operational Testing meets design specification.	2 wks
Total Schedule:	5-6 months
Develop motors for customers	

The MotorPrinter Project Risk Assessment:

MotorPrinter will be developed using a concept fabrication project approach. Although no practical AF-EM 3D-Printer is commercially available or ever built, the risk is rated low by the following assessment:

- ✓ The actual fabrication of the MotorPrinter is straight-forward with critical risk components commercially provided, such as the turn-key fiber laser cutting tool with its self-contained CAD package and XY positioning;
- ✓ With every opportunity, the simple straight-forward MotorPrinter fabrication will leverage readily available off-the-shelf components from auto part stores, hardware stores, hobby shops, etc. to continually reduce the overall design risk and cost of custom components;
- ✓ Although the fabrication is conceptually simple, the USPTO patent process already vetted at least the technical soundness, creativeness, and uniqueness of the patented MotorPrinter by patent attorneys, engineers, and experts;
- ✓ Without reservations or concerns, only approvals were expressed when recently discussing the MotorPrinter technical concepts to technical principles, chief scientists, etc., with potential vested interest, such as electrical steel ribbon manufacturers, fiber laser cutters, etc.
- ✓ Already, a comprehensive cutting study on amorphous material was empirically performed in conjunction with several fiber laser cutter and amorphous metal manufacturers that showed the fiber laser cutter has the highest precision cutting speed, the simplest ease of use, the longest life, and the lowest cutting cost with a satisfactory cut of the amorphous ribbon material and without tooling consumables.