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# THE CASE FOR ELECTRIC MOTORS IN UNMANNED VEHICLES

*Ring Motor.*

Unmanned Vehicles (UV's) that are small enough for a man to carry provide one of the more promising technologies for obtaining live situation intelligence. However, UV's developed for applications, including air (UAV), ground (UGV) or underwater (UUV), with gas or diesel engines may not be practical because of their noise, weight and other application-specific issues. A patented high-efficiency brushless *ring motor* technology developed by ThinGap Corporation of Ventura, California promises to reduce energy consumption, allowing UAV's plenty of flight time once airborne. For UGV's and UUV's, the ring motor can eliminate transmissions, allowing larger payloads, and the ability to move faster, farther or longer between battery charges.

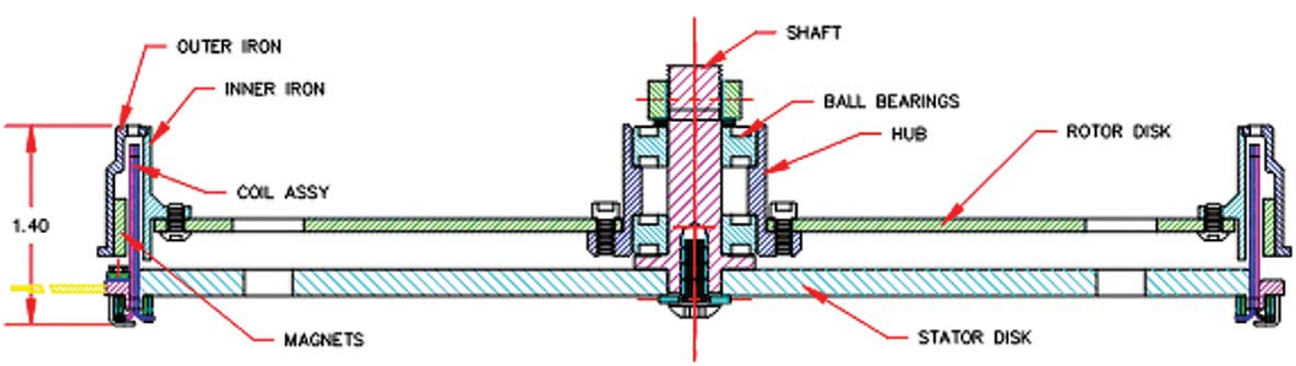
The noise generated by gas or diesel engine UV's deployed for surveillance, sensing and swarming is enough to forewarn the enemy, making the UV an easy target. As a result, information and any element of surprise are lost. The problems extend beyond the noise, which sounds much like an RC-controlled airplane, to include vibration that impairs imaging capabilities and a heat signature that can be picked up by night vision devices. Gas and diesel engines can be silenced with mufflers and special equipment but this increases weight, which affects payload and operational time; and does nothing to improve imaging quality.

Conventional electric motors, such as DC brushless motors, are quiet and light in weight. However, they drain battery packs of substantial current just getting airborne, leaving little current for the flight. In other applications, electric motors have been unable to provide a suitable ratio of horsepower per pound. But a new technology allows electric motors to deliver high power in a small package, which meets the needs of small UV propulsion systems.

## Ring Motor Technology

The unique brushless *ring motor*, designated the TG8250, developed by ThinGap Corporation under DARPA contract DAAH01-03-C-R080, is currently going through further development for a variety of UAV, UGV and UUV applications. The *ring motor* delivers continuous horsepower of 0.80 to 1.3 per pound as well as provides a form fitting platform, which is quiet, cool running, conserves battery power and provides its own gyroscopic effect that reduces vibration and can stabilize UAV's and UUV's.

When taken apart, the *ring motor* looks like a shiny steel ring with an outside diameter of approximately 8.3 inches and a copper colored inner ring with an inside diameter of 7.5 inches. It doesn't look at all like a motor with its large open inner diameter surrounded by the ring that is the motor. This is part of what makes it an ideal solution for ducted-fan, direct wheel and screw drive propulsion.




*Cross-section of the mating rotor ring assembly, consisting of a U-shaped iron channel with a thin wall and magnets mounted to the inside of the outer steel ring.*

In ducted-fan applications, the blades fit within the inside diameter of the *ring motor* and the steel outer ring becomes the airframe over which nacelles or composite structures can be fastened. With its large diameter ring, the motor creates its own gyroscopic effect, eliminating the weight of extra gyroscopic systems. This increases stability, allowing UAV's to fly during rough weather conditions and for all UV's it damps vibration, which improves imaging capabilities.

Understanding ThinGap's unique technology requires a basic knowledge of conventional DC brushless motors. The typical DC brushless motor consists of a rotor and stator. The permanent magnets are mounted to the shaft and rotate, representing half of the magnetic circuit. The stator coil is stationary and made of copper wire wound around iron laminations or other material to support the windings. The other half of the magnetic circuit is next to the coil and remains stationary. The ring motor is fundamentally different from a conventional DC brushless motor in two ways: the coil and rotating parts of the motor.

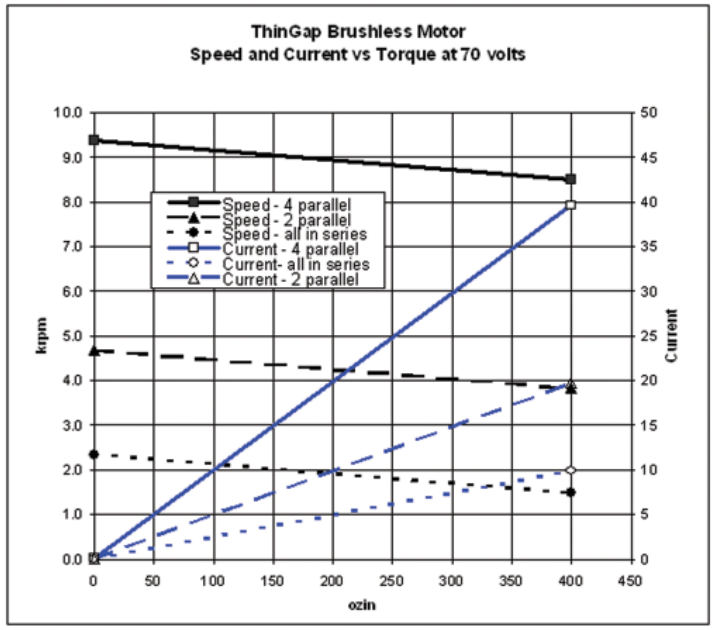
The ring motor coil (stator) replaces wire windings with precision-machined copper sheets formed into a circular coil, allowing a higher copper-packing density than copper wire. The coil assembly has structure without supporting laminations, creating a free-standing coil. The stator assembly can be operated from 50V to 280V by either winding the coils in parallel or in series. The TG8250 *ring motor* is wired to allow 8,750 RPM at 70V by creating a stator with four parallel coils that provides quadruple redundancy. If a coil fails, the motor will continue to operate. Since iron is not used in the coil, inertia and low rotational losses allow the non-operating coil to freewheel, such as in a helicopter blade assembly when it's in autorotation.

The rotor consists of a U-shaped iron channel with a thin inner wall and magnets mounted to the inside of the outer steel ring. The structure forms a channel within the ring that accepts the stator coil. The entire magnetic circuit rotates in the ring motor, which eliminates the iron losses typical of conventional brushless motors. While the only remaining parasitic losses are the eddy current losses (AC losses) that exist in the ring motor's coil, a loss minimized by the coil design.

The rotor features 24 magnetic poles, which provides higher dynamics. Essentially, the number of poles is a compromise between the AC losses in the conductors and the total weight of motor. The more poles in a particular design, the lighter the rotor can be due to the reduction of iron required for the magnetic circuit.

**Different Windings for Different Applications**

By varying the winding configuration of the



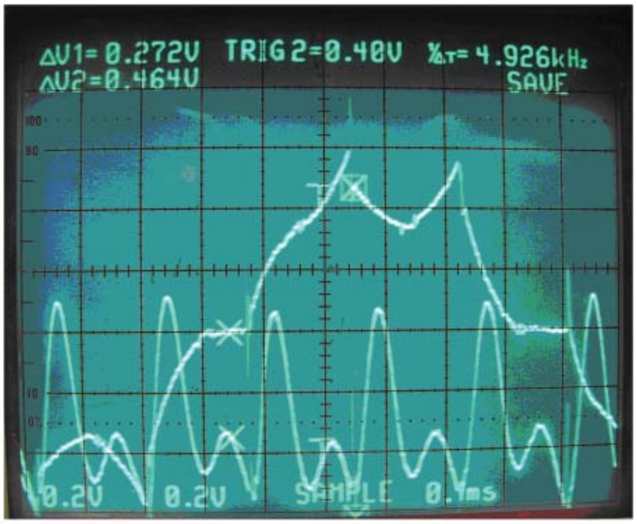

*Speed and current vs. torque for the coil options, including 4 parallel, 4 series and 2 parallel with 2 series coils.*

stator coils, customer-specified speed and torque requirements can be achieved. Different configurations of the four coils were achieved by using parallel and/or series wired circuits. The ability to reconfigure the coils allows the motor to be used in different applications. By making the coil and magnet dimensions longer, the torque per amp increases and the RPM per volt decreases, while HP output more than doubles. For example, torque and total horsepower output can be doubled by lengthening the motor 0.40 inch.

In UUV applications, the *ring motor* can be used as a counter-rotating underwater screw drive motor, providing direct drive for screw drive shafts at 2-4,000 RPM. By using the marine motor cooling system, power output and battery life can be increased.

For four-wheel drive UGV's, the ring motor delivers enough peak and high torque at low speed to eliminate gearboxes and drive trains. The ring motor can be mounted on the wheel to deliver excellent control and maneuverability for direct drive applications.

### Current Waveform



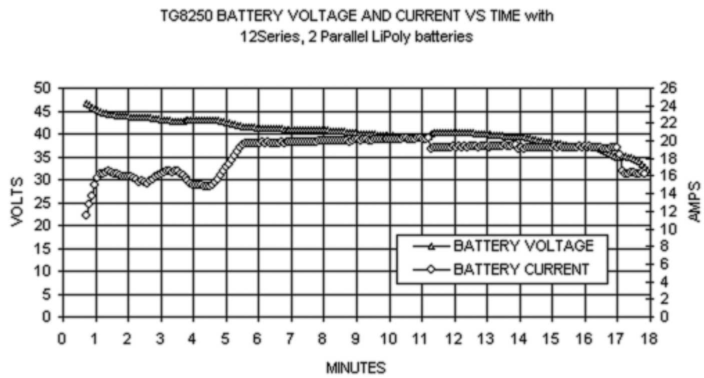

*Bottom trace shows the waveform from DC current into the controllers and the top trace shows the current waveform into the motor phase winding. The top trace shows the rise in current and the decay of the current to zero.*

Traditional motor construction limits the speed a multi-pole iron core motor can reach because its phase waveform cannot switch fast enough at high speed. This is because of the iron core's high inductance. The very low inductance of the ring coil design allows high frequency operation of the amplifiers (high speed switching of the current). This allows more magnets, which creates a higher pole count reducing the mass of the iron to which the magnets are attached. In turn, this reduces the coil weight. With lower weight and higher pole count, the motor has very few limitations on its high speed capabilities. Basically, the current is switched on and off depending on the location of the rotor to create motion, torque and inertia. A conventional iron core motor uses a high-inductance coil, which cannot switch current on and off fast enough to reach its full speed potential.

### Battery Operation

Every UV must have enough battery current to complete its mission with a reserve. UV's in general and UAV's in particular have weight limitations, affecting the size battery that can be used and in turn limiting capacity. In some applications, battery packs are being designed for recharging with portable generator systems carried on HMMWVs. This helps when UV's are used for multiple operations but UV's in general cannot be recharged in the middle of an operation.

The ring motor was tested with lithium-polymer batteries as a power source. The system was tested at 50V, including the battery pack, controller and motor. A dynamometer with a power analyzer was used to measure input power to measured output power of the motor. The power consumed by windage (air or water resistance) is not measured by dynamometer testing because it is not converted to shaft power. For example, a propeller would sustain drag losses, such as in screw or ducted-fan applications.




*The graph shows time of operation to be approximately 17 minutes. The temperature rise of the rotor was negligible and the stator temperature rise was 29 degrees C.*

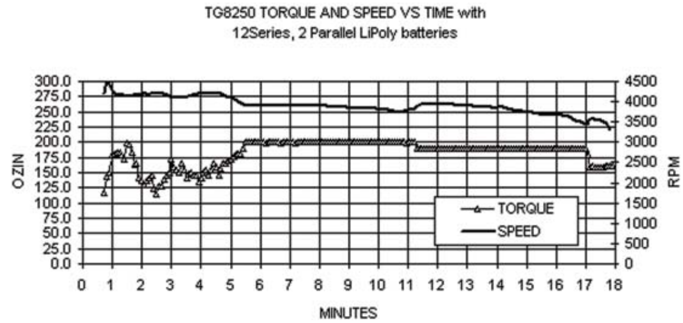
The tests showed the batteries could supply approximately 17 minutes of power before degrading, which is more than enough time for most live-situation intelligence situations. The temperature rise of the rotor was negligible and the temperature rise of the stator was 29° Celsius as bench tested without fan cooling. The lithium polymer battery pack showed strain from a continuous discharge rate of 3C (three times capacity), with one cell pack overheating during each test run. The temperature rise of the battery was about 25° Celsius. The temperature rise of the damaged batteries was 46° Celsius.

Roughness during the first few minutes of operation was attributed to the PID loop (Proportional-Integral-Derivative), which describes the compensation structure used in the dynamometer's closed-loop system. This was a minor operational issue that was tuned on the fly and can be addressed in production. The torque level was reduced slightly at the 11 minute and 17 minute marks.

### Conclusion

The *ring motor* design is extensible with simple length increases of the coil and magnet structure, i.e. 0.40in. / HP. When the length of the motor is extended, the coil design shows that the conductors will be self-compensating for length by gaining width. Therefore motor resistance remains the same as the motor length and HP rating. With the drive current similar in each size of motor, the $I^2R$ losses (power lost in the resistance of the motor windings) remain the same as the HP output increases, resulting in higher efficiency as the motor power output increases. Achieving power output in the four to five HP range appears to be very reasonable and as the motor size increases performance is enhanced.

This *ring motor* configuration appears to be capable of producing the required 1-HP output level with a 7.5-inch inside diameter bore. The capability appears to be closer to 2+HP continuous operating range. Cooling in flight will potentially allow higher power levels to be obtained. The high efficiency performance of the TG8250 allows battery operation. The low heat gain, a secondary benefit of the low-loss design, allows intermittent (such as battery powered) performance at a high-energy conversion level and high power input. The efficiency of the motor remains high over a wide performance range.




*The graph shows time of operation to be approximately 17 minutes. The temperature rise of the rotor was negligible and the stator temperature rise was 29 degrees C.*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