The development of a multi-spectral sensor and unmanned helicopter for the inspection of electrical power lines

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Abstract

In terms of flight modes the ability of a **rotary-winged unmanned aircraft system** RUAS) to hover makes it suitable for applications such as inspection and surveying within localized, access controlled areas. This paper describes the motivation for and development of a robust RUAS and its sensor subsystems, which is being developed at the CSIR so that it can be used in the inspection of electrical pylons.

In the past the research group had designed a portable multi-spectral camera for the inspection of high voltage electrical infrastructure. Initially designed to be hand-held, these sensors were modified for integration with a rotary-winged airframe in order to allow for aerial inspections. This created a need for a rotary-winged aircraft that was capable of carrying the sensors, yet small enough to manoeuvre safely around the infrastructure.

This paper describes the development of the multi-spectral sensor and rotary-winged unmanned aircraft system for the inspection of power lines, a safety system for in field operation and the results achieved.

1. Introduction

Electricity is clearly important for industry. In South Africa during January 2008, industrial plants were regularly shut down due to power supply interruptions. According the SA Chamber of Commerce this has cost the country R8.5 billion (billion Rands) in income.

A transmission line consists of a tower which supports the conductors by means of insulators.
In addition to providing insulation from the high voltage line the insulators need to support the line. If the insulator fails electrically or mechanically, a short circuit could occur and the line would drop to ground resulting in a power outage.

Over time the insulators may crack or break due to wear or environmental conditions such as fungal growth on the insulators. Internal cracks in the insulators can be very difficult to detect. Another common problem is partially broken connections at various junction points. Such broken connections may not be easily detected through visual inspection alone since the transmission lines have multiple strands and some strands within the bundle may break making them difficult to detect.

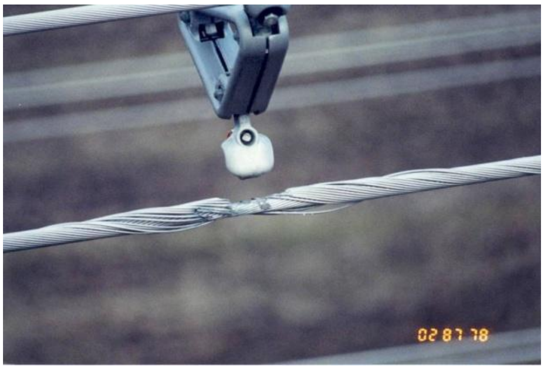


Figure 1. Transmission line defect – partially broken strands

In South Africa there are 381 700 kilometres of transmission and distribution lines that need to provide a continuous supply of electricity. This can only be assured by the regular inspection of the transmission lines and their components such as insulators, mechanical clamps and the tower structure or pylon. Eskom has developed an inspection and maintenance programme that is executed at a regional level.

Currently, the inspection of the pylons and the servitude is performed in one of two ways. The first involves sending a two-man crew, equipped with a standard camera, to drive along the lines and perform the inspections from the ground. This limits the view of the insulators and sometimes the terrain can be difficult to cross. These foot patrols are carried out once per year.

Figure 2. Inspections from the ground can be impeded by difficult terrain.

Another way involves performing the inspection, from a manned helicopter, again using a standard camera. This, however, gives the inspector a view from above only. This solution is costly and maneuvering around the pylons can be dangerous. Helicopter inspections are performed once per year for non-critical lines and three times per year for critical lines.

Vegetation encroachment at power line servitudes is believed to be the biggest cause of storm related ignition. Monitoring the servitude is a slow and costly process. The inspection crews need to assess the severity of the vegetation encroachment and take a decision on its treatment.

In South Africa, the electrical utility, Eskom, in recent years has had to reduce aerial scanning due to the high costs. The operating cost of a manned helicopter equipped with a gimbal (stabilised camera platform) containing infrared and visible spectrum cameras is typically R12 000 per hour in addition to the hourly cost of the utility's crew. The total line inspection cost at a national level is significant. In order to create a more effective and optimal inspection system, the CSIR began developing a rotary-winged unmanned aerial vehicle (RUAV) equipped with the necessary sensors for inspecting power lines.

2. Inspection Sensors

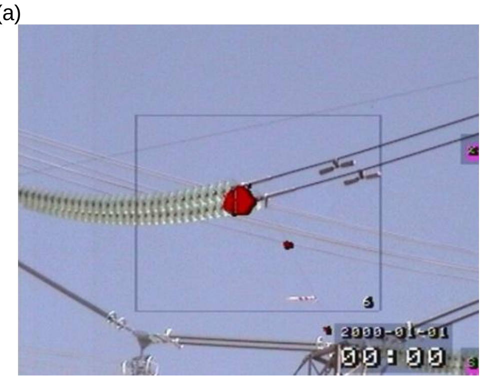
The CSIR had developed specialized diagnostic camera systems for the inspection of transmission and distribution lines. These cameras could locate potential line defects by detecting and analyzing corona activities. The CoroCAM camera series is one such example which has received positive responses internationally.

The inspection of a transmission line also requires the detection and location of thermal hotspots which indicate poor conductivity that often leads to burn outs and thus power outages. This requirement led to the incorporation of an infrared detector into the existing corona detection camera so that it could detect and analyze thermal hot spots. This was the start of the development of the multi-spectral camera.

The multi-spectral camera developed at the CSIR allows the user to view an inspection area in three spectral bands. The three bands range from the short wavelength ultraviolet spectrum (240 nm to 400 nm), the visible spectrum (400 nm to 780 nm) and the far infrared spectrum (8 µm to 12 µm).

By examining the components of the power lines in each of these bands, one is able to detect various defects. For example, corona discharges are detected in the ultraviolet band while emerging hot spots due to poor connections are detected in the infrared band. The information about the defects is then correlated with and overlaid onto the image in the visible spectrum thereby highlighting the defect.

(a)



(b)

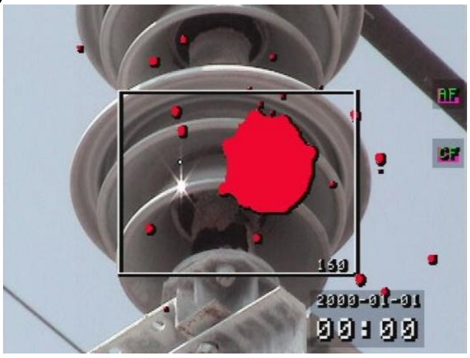
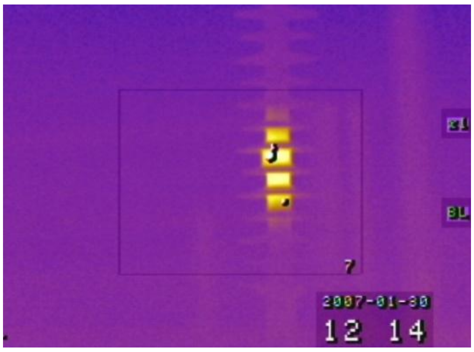


Figure 3(a) and (b). Corona which is invisible is detected on the insulators and highlighted as red blobs.

Corona discharges are typically associated with cracked or broken insulators, missing corona rings or broken ground plate connections. By analysing the amount and distribution of the corona effects one can detect these faults. As an example, figure 3(a) shows a ceramic insulator being inspected in the ultraviolet band using the multi-spectral camera. The red blob indicates that corona has been detected at the live end of the insulator and this degree of radiation typically indicates a missing corona ring. Figure 3(b) shows that significant corona radiation has been detected at earth level and this typically indicates either fungal growth or a cracked disc.

(a)



(b)

Figure 4(a). Hot-spots are detected in the infrared band. Figure 4(b). The infrared information is overlaid onto a visible spectrum image.

The infrared spectral band allows the detection of hot-spots on the transmission line and these are typically interpreted as broken connections. When a break occurs, the current has to flow through a thinner area which causes heating. Figure 4(a) shows that corona has been detected on the third disc from the live end. Figure 4(b) shows the same composite insulator but this time with information in the infrared band. This distribution of corona and hot-spots typically indicates that there is an internal crack in the disc. This cannot be diagnosed from an inspection using a normal camera alone. The above examples demonstrate the operation and effectiveness of the multi-spectral camera.

3. RUAS for Inspection Applications

There are a number of applications for which one could use unmanned aircraft systems (RUAS's). They could be used for surveillance in policing applications and for situational assessment in search and rescue applications. In the agricultural industry they could be used for crop analysis and crop dusting. They could also be used in the entertainment industry for aerial photography and filming.

In inspection and surveying applications rotary-winged unmanned aircraft systems (RUAS's) have an advantage because of their unique flight modes. They give flexible and localised access to the three-dimensional airspace and allow for stationary observation. The localised access implies that the risk to other air traffic is reduced since the RUAS can be operated in the line of sight. In terms of the inspection of power lines it can be used as a tool to extend the viewpoint of the operator – allowing the operator to observe the point of interest from above and below. This makes it a more effective solution. It is estimated that the operating cost of a RUAS based inspection system would be about $350/hour.

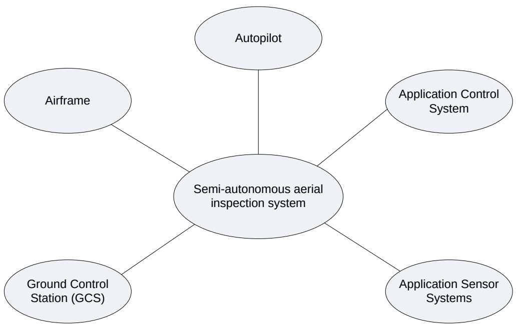


Figure 5. Technology building blocks for semi-autonomous aerial inspection system

Figure 5 shows the main technology building blocks of the aerial inspection system that was developed. The research focused on the development of the airframe, the application sensors and a safety system. This is described in section 4. The results achieved in these components are described in sections 4.3 and 5.

4. System development

4.1. Airframe development

The main specifications that were used to guide the development were as follows:

- One hour flight endurance
- Payload of 8 kilograms at 1500 meters above sea level
- Gross mass of 25 kilograms
- Length of less than 2m (to enable safe manoeuvrability between power lines)
- Easy maintenance and operation
- Autonomous flight with GPS waypoint navigation (to support programmable flight patterns)

The development of an airframe capable of lifting 10 kilograms at an altitude of 1500m above sea level proved to be a bigger challenge than originally envisaged because both rotor performance and engine power are adversely affected by the reduced air density at an altitude of 1500m compared to sea level.

The Gesso Myers [1] estimate indicated that for the characteristics of this rotorcraft the main rotor power requirement to hover out of ground effect at a gross mass of 25kg at local conditions in Pretoria, South Africa, was 2.2kW. The tail rotor power requirements varied somewhat according to the particular configuration and design but a figure of 10% of the total power was typical. In addition, the power required to drive the rotors was required to overcome the losses in the drive train. Losses may be estimated at 0.5% per gear pair [2]. Therefore assuming the equivalent of five gear pairs the drive train loss would be 2.5% (or 97.5% efficient). The estimated total power requirement was thus:

$$Power = \frac{(P_{mr} + P_{tr})}{\eta_{drivetrain}} = 2.5kW \quad \text{(Equation 1)}$$

The minimum power level required is about 2.5 kW and needs to be increased by any excess power margin requirement. If the operation at an altitude of 1500m is required this requirement will similarly increase.

At first an XCell airframe based helicopter powered by a 50CC petrol engine with a rated output of 8.5 HP (6.32kW) and a head speed of 1480rpm was developed but due to the vibrational forces created at its natural frequencies, further work was halted.

Next a turbine driven helicopter platform was developed with an 8.5HP (6.32kW) Wren motor. The turbine had sufficient power and torque to lift a payload of 13 kg. However the fuel consumption of 130ml litres per minute (7.8 litre/hr) made the turbine impractical to use for flight durations of greater than 30 minutes.

A third airframe was built with two opposite aligned 26CC petrol engines. Performance data in terms of a torque curve and engine speed was sought from the Evolution engines web site [3] for the Evolution 26GX. However this information was not offered for the Evolution engines line. The maximum power and torque figures for the 26GX engines are listed in the owner's manual [4] as:

- Maximum power output 3.8 HP / 9000 RPM
- Maximum torque 2.18ft-lb / 8000 RPM

Assuming a density ratio (local/sea level) of 0.83, which is applicable to local conditions in Pretoria, these two figures may be revised to

- Maximum power output 3.17 HP (2.36 kW) / 9000 RPM
- Maximum torque 1.82ft-lb (2.49 Nm) / 8000 RPM

Based on this published performance data the available power from the twin engine configuration should have been 2x2.36 kW, or 4.7 kW in Pretoria (allowing for density effects). This is far in excess of the estimated power requirement of 2.5 kW indicated by Gesso and Myers' rapid performance estimate.

Extensive field testing was done but, while in ground effect (IGE) operation was achieved, sustained out of ground effect (OGE) operation at the desired take-off weight was not possible. Subsequent bench testing at the CSIR achieved power levels ranging from 2.3kW to 2.7kW. The effect of the tuned pipes on overall power was shown to be of order 25% by comparison with power achieved with "short stack" type exhausts. Marginal increases in power were achieved with modification to tuned pipe length but the levels were substantially lower than the specified 4.7kW.

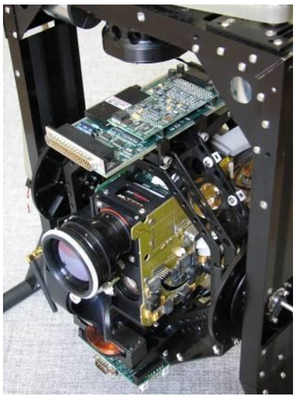
The team decided to abandon the 26CC engines and to proceed with testing and evaluating the next in the series of the Evolution engines, the 40GX - a 40CC single cylinder petrol engine. Bench testing showed that a 40CC engine could deliver 2.5kW at 7900 rpm with an appropriate tuned pipe. A twin power-plant configuration with two Evolution 40CC engines should therefore be able to deliver in the order of 5kW. Factoring in estimates for drive train losses and power absorbed by the tail rotor will see this reduced to approximately 4.4kW. Power levels under operation without tuned pipes would be expected to be reduced by about 25% to about 3.1kW. This is the approximate power level expected to be available to the main rotor in Pretoria conditions at ground level. Operation at altitude in Pretoria can be considered to represent a "hot and high" operation. These conditions are typically handled by a temperature increment applied to the International Standard Atmosphere (ISA). A representative "hot and high" density altitude for 6000 ft (1828.8m) in the Pretoria area would be ISA+30, i.e. density at an altitude of 6000 ft (1828.8m) but at a temperature 30°C greater than the equivalent ISA temperature. This will reduce the available power to 2.8 kW and the available lift from the rotor is expected to be 280 N for a maximum take-off weight of about 28.5 kg with no excess power allowance.

Extensive endurance tests were conducted and the new engine configuration could comfortably lift the frame of 13.5 kg with three litres of fuel (2.5 kg in weight) and an 8.5 kg dummy load. This resulted in an effective lifting capacity of 24.5 kg. More than an hour of flight has successfully been conducted with a fuel consumption of two litres and maximum recorded engine temperature of 112˚C.

4.2 Sensor System and Ground Control Station

The multi-spectral camera was integrated into a stabilised and articulated gimbal. The gyro based stabilisation platform has azimuth drift of 144˚/h (2.4˚/min) and elevation drift of 57.6˚/h (0.96˚/min). Both specifications are sufficient to guarantee stable recordings of a power line structure with 50Hz based camera sensors. Figures 6(a) and 6(b) show the stabilized gimbal that houses the camera sensor.

6(a)



6(b)

Figure 6(a) and 6(b). Stabilized gimbal to house the multi-spectral camera

The gimbal transmits video telemetry and receives control commands from a ground control station which is shown in figure 7. The communications link operates at a 2.4GHz frequency.

Figure 7. Ground control station

4.3. Safety System

The system is currently remotely piloted but it is envisioned that an on-board autopilot that supports manual (by an operator) and GPS based positioning will be incorporated. In the field the aircraft will fly in close proximity to the structure in order to obtain optimal inspection data. However it is likely that the operator's perception of depth (with respect to the helicopter's coordinate frame) would be compromised from a remote location. Therefore in order to ensure safe operation it would be desirable to have a localized obstacle detection system to alert the operator of potential dangers.

The researchers developed a system that used laser input data from a laser scanner to provide this functionality. The system was developed on an autonomous ground vehicle (AGV) during the research stage with the possibility to port it to the aerial vehicle.

The system used a version of the Extended Kalman Filter Simultaneous Localization and Mapping algorithm (EKF-SLAM) [5]. The algorithm enabled the vehicle to develop and maintain a feature map of its localized (initially unknown) environment and to further determine its position with respect to this map in real-time. In addition an environmental proximity map was also created by registering the laser scans to the feature map and vehicle positions. The proximity map is what is sent to the operator so that the proximity to the local structures can be determined.

It was found that an update of laser scans alone would normally be from the point of view of the vehicle and this could be disorienting to the operator and lead to possible errors in judgment. However when registered with respect to the stationary structures ie. the features, the operator can use this fixed reference frame to make more accurate judgements about the vehicle's local environment.

The system was implemented and evaluated and the results are summarized in the graphs in figure 8. The black graph shows the actual path (ground truth) traced out by the vehicle as measured by an external sensor. The red graph shows the path as determined by the EKF-SLAM algorithm. It was found that the areas of higher correlation corresponded to areas in the physical environment that contained more features to help the location. This result is expected with EKF-SLAM.

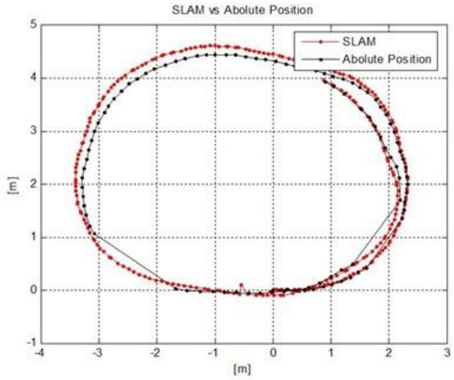


Figure 8. EKF-SLAM results.

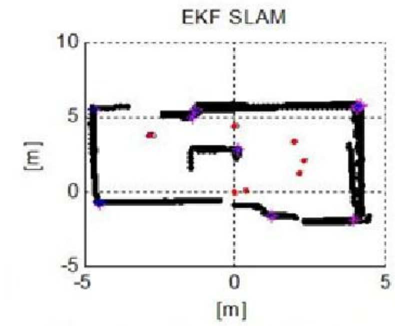


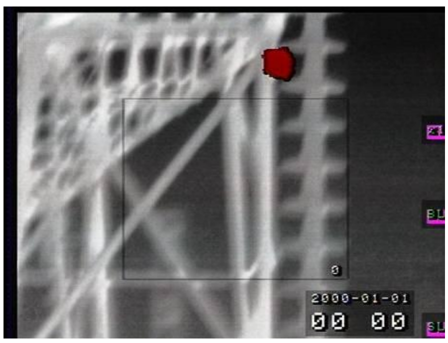
Figure 9. EKF-SLAM derived proximity map

Figure 9 shows an example of a proximity map that was derived by the vehicle using the EKF-SLAM algorithm. This is typically what would be presented to the operator to help in determining the localized structure of the environment.

5. Evaluation of the RUAV

Line inspections were conducted at a high voltage test station in order to determine the influence of the electro-magnetic field onto the RUAS avionics, gimbal and multi-spectral camera controls. Provisions were made to reduce the effect of electro-magnetic interferences by shielding the electronic circuits of the avionics, the gimbal and camera controls. At first the line was energised at a low voltage of 60 kV. The line voltage was then gradually increased up to 240 kV and observations of the control and behaviour of the helicopter and sensors were recorded.

(a)



(b)

Figure 10(a) and (b). Recordings of glass insulators, single and double string with oxidised sections, as captured from the stabilized multi-spectral camera.

Figure 11. The RUAS flying 4 m above ground with a total lift weight 25kg

Currently the RUAS as shown in figure 11 is remotely piloted, with a total lift capacity of 25kg (airframe, fuel and payload) and it was able to fly for one hour on a single tank of fuel. The endurance test was carried out in intervals of ten minutes to allow the test pilot a break in between.

6. Conclusions

- The development of a rotary-winged UAS platform for the South African environment capable of flying at 1500m altitude for one hour and with a payload capacity of 8.5 kilograms, and length of less than 2m has been successfully achieved.
- The sensor system with its stabilized gimbal housing and ground control station for inspecting power lines was developed.
- The safety system to help the pilot to understand the structure of the localized environment around the airframe was developed and has shown promising results.
- The RUAS currently flies under remote control. An autopilot will be integrated in the next stage of the project to enable autonomous flight control with GPS based waypoint navigation. It was decided to purchase and integrate an off-the-shelf autopilot into the system since these are available both locally and internationally.
- The next stage of the project will also involve the integration of the stabilized sensors now that the testing with test loads has proven successful.

7. Acknowledgement

The authors acknowledge their employment organisations for their continuous support in the development of the RUAS for the inspection of power lines and for providing the test facilities to evaluate the performance of the system. The authors also acknowledge the National Research Foundation NRF and its THRIP program and the electrical utility Eskom for their continued support.

9. References

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