Development of e-Juba, a preliminary proof of concept unmanned aerial vehicle designed to facilitate the transportation of microbiological test samples from remote rural clinics to National Health Laboratory Service laboratories

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For students and academics within the field of Medical Microbiology and Infectious Diseases, it is readily apparent what an enormous professional contribution Professor Hendrik Koornhof has made to this critically important specialty, not only in Africa, but worldwide. For those outside of the specialty, his contributions as a thoroughly decent person and role model are no less evident. What emerges in both spheres is his clear commitment to the welfare of others, as opposed to himself. His modesty and self-effacing nature have endeared Hendrik to many generations of students, peers and others who have indeed been privileged to have benefited from knowing him and working with him.

In his 50 years with the South African Institute for Medical Research, and subsequently with the National Health Laboratory Service, Hendrik Koornhof has been the ideal academic, who is not as concerned about receiving financial rewards, recognition, etc. as about contributing to scientific knowledge. Many of his contributions have been in guiding others by his words and his deeds, and as a result he has been rewarded in seeing the accomplishments of his students, many of whom have gone on to achieve greatness in diverse fields, both locally and abroad.

As we reflect in this festschrift on Hendrik's many achievements over 80 years, we thank him for more than just his research and teaching contributions over half a century with the South African Institute for Medical Research and the National Health Laboratory Service. We thank him for showing us what a privilege it is to work in the world of academia. Although we are not microbiologists, we thank him for having inspired us with the will to address problems of service delivery in the fight against microbiological diseases, which constitute the overwhelming bulk of the burden of disease in the developing world, both in Africa and further afield.

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The HIV/AIDS pandemic currently ravaging sub-Saharan Africa is placing severe demands on laboratory services in the subcontinent, both in its own right and also in consequence of the attendant epidemic of TB and opportunistic infections. These are all laboratory-intensive diseases, whose optimal treatment is not amenable to the clinical syndromic management approach. These demands are particularly severe in remote rural areas, many of which lack basic infrastructure such as landline telecommunications, ESCOM power supply and adequate roads. Logistics in such areas are usually the rate-limiting barriers to effective laboratory service delivery.

The e-Juba (electronic pigeon) project is an experimental, joint undertaking between the National Health Laboratory Service (NHLS) and Denel Dynamics (UAV division), to address the afferent, pre-analytical phase of the laboratory logistic loop, viz. specimen transport, in remote areas. Typically, centralised laboratories at the hubs of such areas serve approximately 20 clinics each, which are located approximately 10 - 30 km distant. For a variety of reasons, reliable transportation between such hubs and their spokes has traditionally been refractory to conventional solutions, including courier services, taxis, ambulances, motorcycles and even helicopters. Based on the precedent of carrier pigeons, which have been used with partial success to transport medical samples in rural areas, the concept of the electronic carrier pigeon was developed to overcome the 'one way' limitation of natural carrier pigeons.

This report describes the specifications and preliminary trials of e-Juba, a mini-unmanned aerial vehicle (UAV) designed to transport a payload of up to 500 g over a distance of up to 40 km via multiple Global Positioning System (GPS) Lat/Long/Alt waypoints to a specified target. The conception and design of the aircraft and its payload have been guided by recent developments in the following: **molecular diagnostics**, which facilitate reduction in sample size and novel dried spot format to eliminate biological hazard and to bypass the cold chain; **lithium polymer chemistry** for low-weight batteries; **brushless electro mechanics** which enhance the efficiency and reliability of electric motors; **GPS** and **differential GPS** technology to facilitate unmanned navigation; micro-electromechanical systems (**MEMS**) technologies for miniaturised inertial guidance systems including three-dimensional gyros and accelerometers to facilitate autonomous aircraft stability; **ultrasound** ground detection technologies; multiple other onboard detectors and telemetric devices, and the **GSM** data wireless networks for post-analytical communication of results.

The South African health care service comprises approximately 6 000 clinical facilities, ranging from large academic hospitals in metropolitan areas to small primary care clinics in remote rural areas. Many of the latter are located in parts of the country lacking even such basic infrastructure as electricity supply and fixed landline telecommunications. Roads to these remote clinics are generally poor and often unserviceable. Such logistic difficulties are common in developing countries around the world. Supplies of blood and laboratory services are invariably problematic in such areas, and can become the rate-limiting factors in effective health care delivery. This is especially so in view of the current epidemics of HIV/AIDS, tuberculosis and malaria, which are particularly prevalent in sub-Saharan Africa. These are all laboratory intensive diseases, whose diagnosis and monitoring is critically dependant on data, which cannot be obtained from clinical history or examination. Unlike many of the primary care disorders that historically constituted the bulk of the clinical load in such clinics, and which could be managed syndromically, HIV/AIDS, tuberculosis and malaria all require technologically based investigations for their optimal management. Point of care (POC) testing methods address this need, but failure to achieve economies of scale has limited the cost effectiveness of such solutions.

This communication reports progress made in developing proof of concept of a number of technologies targeted to provide novel logistic solutions to problems of laboratory service delivery in remote rural areas. The technologies deployed are divisible into those that address problems of transportation of diagnostic samples, and those addressing problems of data telecommunications.

Transport

The ±6 000 clinical facilities in South Africa are currently served by some 300 public service laboratories, most of which fall within the National Health Laboratory Service (NHLS) network. This equates to a ratio of approximately 20 clinics per laboratory. This can be visualised as 20 spokes per hub. Transportation of diagnostic medical samples from remote rural clinics to more centralised laboratories potentially offers a cost-effective approach to service delivery by centralising expensive equipment utilising batch processing systems to harness and manage economies of scale. Methods used to provide this physical transportation network include traditionally in-house or outsourced courier services operating predominantly two- and four-wheeled motorised vehicles. Fixed and even rotary winged aircraft may be indicated in some instances, particularly where distances are large, as for instance in the Northern Cape, or where road quality is poor, which is especially problematic in the eastern part of the Eastern Cape, and some parts of Mpumalanga and Limpopo provinces. In these regions, comparatively close facilities may effectively be cut off from one another by adverse terrain, especially following heavy rains, when gravel roads deteriorate markedly. It is to explore possible solutions to transportation problems in this type of terrain that the current feasibility study to investigate the development and deployment of UAVs was initiated, because rotary winged aircraft are prohibitively expensive and dangerous to pilots and ground personnel.

UAVs are seeing increasing application worldwide, mainly in the military sphere, where manned aerial missions are 'dull, dirty or dangerous'.[1] Although payload delivery missions are practical, applications currently are chiefly of a surveillance nature, and although these are predominantly for tactical military or strategic geopolitical purposes, there is a fledgling interest in non-military applications.[2] Examples include agricultural surveillance, especially in the viticulture industry, where aerial infrared surveys have contributed to management decisions concerning crop harvesting.

UAVs typically comprise an airframe, a propulsion device, and avionic systems. Airframes range in size from less than 1 metre wingspan (MicroUAV) to massive high-altitude long-endurance (HALE) aircraft weighing several tons and with wingspans in excess of 20 metres. This communication describes the design specification and preliminary test flights of e-Juba (electronic pigeon), a NHLS-Denel Dynamics joint venture to develop a UAV capable of transporting a payload of up to 500 g over a distance of 40 km. The payload is specified to accommodate medical diagnostic samples, but could also be applicable to carrying urgently required medications such as rabies immune globulin, anti-snakebite serum or packed red cells (the current e-Juba airframe could be modified to carry a maximum of two units, whose weight would not exceed the payload design specification). To eliminate biohazards posed by infectious body fluids, the project envisages the use of dried spot technologies coupled to molecular diagnostic methodologies, which are already in widespread service within the NHLS. Denel Dynamics have 25 years of experience in the design, manufacture, operation and sales of sophisticated UAV systems.

The propulsion method for UAVs may be based on gas turbine, conventional internal combustion or electric power systems. Recent developments in battery technologies have rendered electric power an entirely suitable modality for small UAVs. These include lithium polymer (LiPo) batteries based on lithium chemistry, which have enabled significant improvements in battery capacity, as measured in milliamp hours, per gram of mass, over traditional nickel metal hydride, nickel cadmium or lead plate accumulators. In parallel with these developments, electric motors employing electronic brushless current distribution systems, instead of mechanical commutators, have dramatically improved the efficiency, power to weight ratios and reliability of such motors, in comparison with traditional electric motors. Preliminary e-Juba test flights were conducted with a commercial off-the-shelf (COTS) airframe and internal combustion motor, but the current prototype is powered by a LiPo powered brushless motor.

Avionic systems for UAVs are centred on navigation systems utilising the Global Positioning System. The widespread commercial deployment of GPS devices has effectively commoditised this technology to a level where programmable low-cost, high-reliability navigation is generally available. In addition to unmanned navigation, UAV avionics also include systems to govern autonomous flight stability, which include three-dimensional gyros and accelerometers, electronic compasses, and ground detection technologies (AGL) based on ultrasound emitters and detectors. The latter technology is required for the precision demanded of autonomous landing missions. E-Juba is currently guided by the imported commercially available MicroPilot™ system, which integrates all these functions, and includes barometric altitude and airspeed determinations (Fig. 1). The basic GPS pilot (excluding antenna), barometric sensors and flight stability systems weighs in at only 28 g. Up to 1 000 waypoints, defined in 3D space as latitude/longitude/altitude, may be programmed into the pilot for autonomous low-level guided flights over complex terrain contours. Comprehensive on board radio-based telemetric functions are also provided in the various prototypes to permit ground-based monitoring of flights in real time. These will be omitted from the final implementation to save weight and cost, but actual telemetric readouts from a test flight are presented in this communication (Fig. 2).

Preliminary proof of concept trials with the custom built airframe (Fig. 3) have demonstrated successful autonomous takeoff, autonomous GPS guided flight via three-dimensional

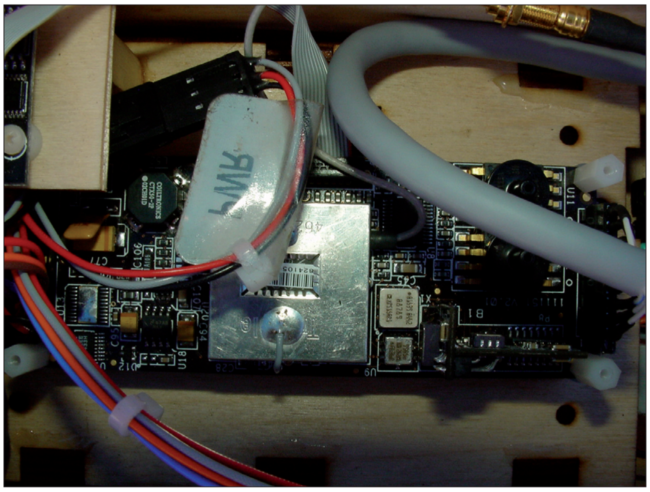

Fig. 1. MicroPilot™ system in situ. *GPS navigation, programmable IT hardware, telemetric outputs and flight stability devices are incorporated, while barometric inputs for altitude and air pressure from airspeed pitot tubes are visible at right. The electronic compass module is at top left of picture. The AGL circuitry, radio receiver and radio telemetry transmitter, electromechanical servo's and power supplies are not visible in this view, but all are accommodated in an airframe weighing 3.5 kg in total, including propulsion unit, batteries, avionic systems and full payload.*

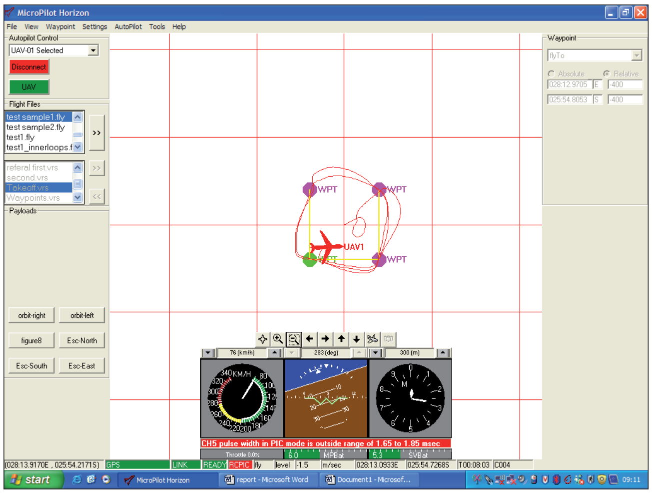

Fig. 2. Horizon $_{mp}$ *software screen dump from real time tracking of a UAV test flight, as despatched by onboard telemetric radio and received at ground base station. The UAV has completed 2.5 circuits, each of approximately 1.6 km of a 4-waypoint course. In flight data include previous track, current position, course, airspeed (approximately 70 km/h), artificial horizon (showing a right bank) and altitude (270 m above ground level). Real-time ground visualisation of on board video capture is an option, not currently installed in e-Juba, along with grid-referenced terrain mapping. The data are from a test flight of a COTS product lacking deliverable payload capacity. Because the demonstration flight employed manual takeoff and landing, switching in-flight to autonomous flight control under GPS navigation, it is classified as a UAV/RPV (remote piloted vehicle) hybrid mission. Although the specifications and design include full autonomous takeoff and landing capability, cost considerations are likely to favour this hybrid UAV/RPV format in final implementations.*

Fig. 3. e-Juba on launching ramp. The cargo bay for medical samples is in the fuselage directly below the wing, to obviate centre of gravity shifts when loading samples. Maximum payload is 500 g.

(latitude/longitude/altitude) waypoints, a range of up to 53 km, and autonomous landing capability. Further trials will be focused on improving reliability sufficiently for field use.

Telecommunications for post-analytical communication of results

Although lacking access to the Telkom landline telecommunications network and Escom electric power grid, clinics in remote rural areas of South Africa are generally well supplied with wireless communication signal provided by one or more of the three Global System of Mobile (GSM) network service providers.

Access to the GSM networks enables access to wireless data communication via the short message service (SMS) and general packet radio service (GPRS) systems. In most cases medical laboratory reports can be despatched by simple push technology SMS,[3] and more sophisticated duplex data communication is possible using interactive SMS, GPRS or Universal Mobile Telecommunication System (UMTS), or 3G.

Because of refractory problems with turnaround times for the TB microscopy diagnostic service, a 2-year pilot study was carried out in the Port St Johns region from 2001, using SMS reporting systems for the rapid communication of TB microscopy results. When coupled with provision of a reliable, though dangerous, motorcycle-based transportation system for medical sample collection from remote clinics and delivery to the laboratory, application of SMS reporting technology was associated with an appreciable increase in the proportion of patients successfully treated for *Mycobacterium tuberculosis* infection according to the directly observed treatment – short course (DOTS) strategy. SMS reporting systems can be achieved from handsets, or incorporated within laboratory information systems based on desktop PC or mainframe server hardware architectures. Per report costs of transmission in bulk are negligible, while the cost of reception is non-existent, given the availability of a handset at the receiving clinic. Potential value-added services include reporting of messages successfully delivered to destination, together with logging of times. These are important QA data for audit trail purposes.

Conclusion

Proof of concept has been obtained for a variety of novel transportation and communication systems to address logistic difficulties experienced by clinical laboratory services in remote rural areas of South Africa. Reliability will have to be improved before the potential benefits of this approach can be fully realised. Some of these concepts could become relevant to similar logistic problems confronting clinical service providers and blood transfusion services, as well as diagnostic laboratories located in other developing countries.

The authors wish to acknowledge Gavin Penkin of Exactmobile for setting up the prototype SMS reporting module and Dr Rudi Thetard for the clinical data from the clinics in the Port St Johns area.

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