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UAS EDITION

UAS for Mapping

A Survey on Systems and Features

Robots in Surveillance

Safe Navigation for Autonomous Robot Systems

UAS in the Andes

Determining Volume Changes

GIM International Interviews

Peter Cosyn

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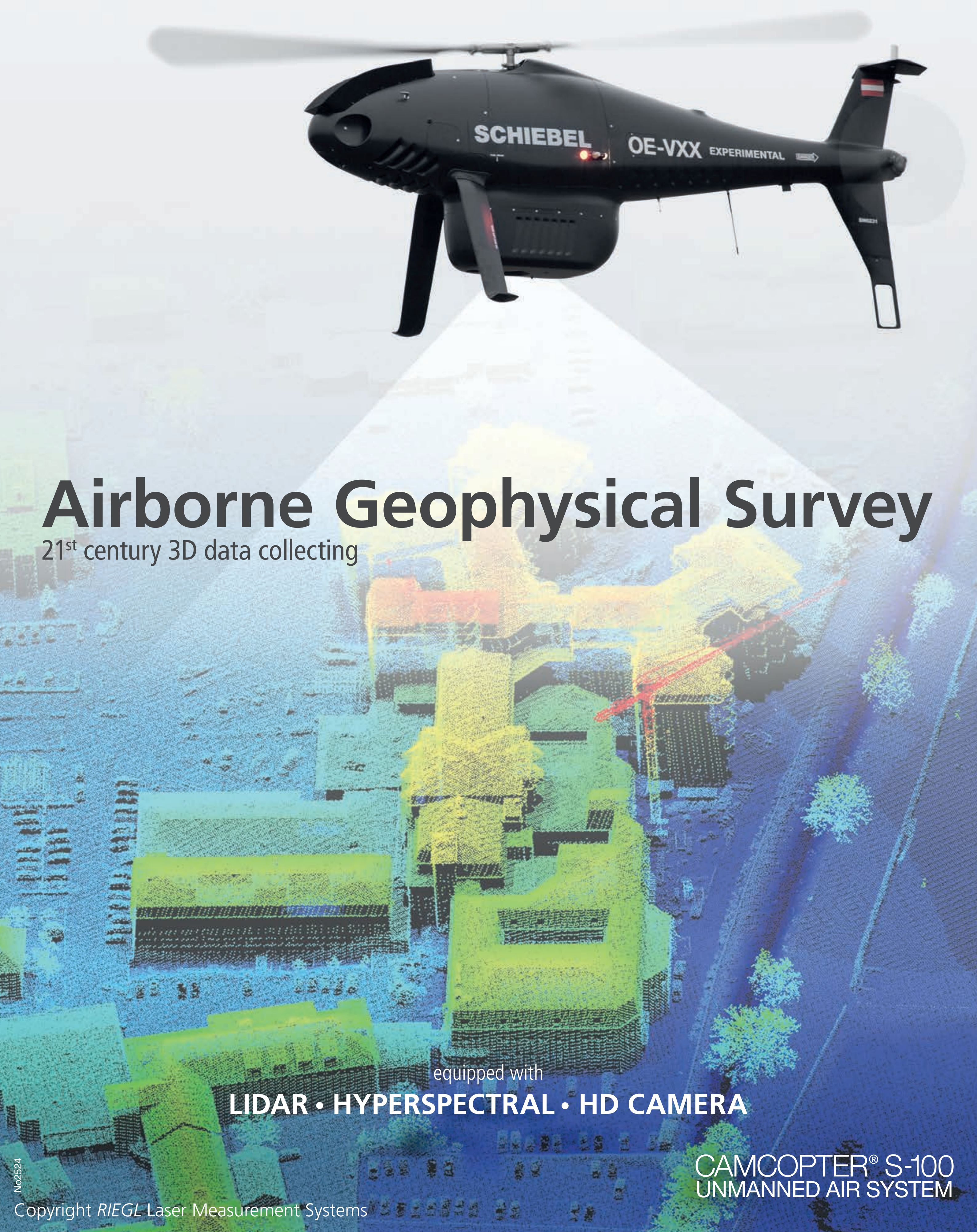

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Groundbreaking

This is the second time *GIM International* has published a special issue dedicated to the technique of unmanned aerial systems (UAS) for geomatics. Our first issue in August 2013 was very well received by readers from all over the globe, so we decided to publish this second edition, this time in spring – celebrating the start of the new flying season (at least in the northern hemisphere). In August last year, I called UAS a "groundbreaking" technology. It has certainly proven to be groundbreaking, and disruptive. At the same time, the technology is maturing rapidly, settling in amongst all those other surveying techniques – both terrestrial and airborne. Further proof of this maturing process is the fact that all major producers of surveying hardware have acquired a company – often a start-up – that specialises in UAS: Trimble bought Gatewing a couple of years ago, Topcon announced a strategic partnership with MAVinci some months ago and Leica Geosystems has firmed its alliance with German UAS manufacturer Aibotix in the last 18 months. We will undoubtedly see this process continue in the near future with other start-up companies growing or being acquired by bigger producers. The same goes for the further development of the technique, as underlined by the array of articles in this special edition. First of all, an overview article by our senior editor Mathias Lemmens (see page 12) will bring you up to date on all the systems currently available on the market. For an insight into the evolution of one of the industry forerunners, Gatewing (now Trimble UAS), please read our interview with developer and co-founder Peter Cosyn on page 6. Amongst others, we are sharing with you several original feature articles. Christian Fiermann, Oliver Kurz and Franziska Klier of the Fraunhofer Institute in Germany have developed an unmanned ground system which – using GNSS and other positioning devices – accurately follows a pre-specified path while avoiding obstacles to work in tandem with an unmanned aerial system (see page 26). Additionally, Eric Romersa and Olivier Küng shed light on the possibilities to determine volume changes in the Chuquicamata open-pit mine in Chile using UAS in their article 'UAS in the Andes' on page 19. And there's even more…! I cordially invite you to read up on all the latest developments here, and also to take a look at www.gim-international.com where you will find more news, background information and videos about UAS. If you've not done so already, why not subscribe to *GIM International* to ensure that you automatically receive up-to-the-minute geomatics news delivered to your door and/or your inbox from now on. I'm looking forward to hearing your feedback on our second UAS special.

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Photography: Arie Bruinsma

The front cover of this edition of *GIM International*'s UAS Special 2014 shows the eBee UAV from senseFly. In 2013 the company demonstrated that UAS mapping technology is capable of producing a digital 3D model of the Matterhorn, one of the iconic peaks of the Swiss Alps, in 20cm resolution.

GIM INTERNATIONAL
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UAS Around the World

As editor of this special issue of *GIM International* I am delighted that the success of the first edition dedicated to UAS, published in 2013, has resulted in this follow-up issue. Unmanned aerial systems have been operational for regular geodata collection for some time now. One example is the weekly capture of a nuclear power plant construction site in the UK using a fixed wing – wingspan 100cm; weight 2kg – as reported in the first UAS special

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edition. Here, on page 19, Romersa and Küng present the use of the senseFly eBee fixed wing, equipped with a customised 16MP Canon Ixus 125HS camera, for creating a digital surface model (DSM) of the world's biggest open-pit copper mine. From time series of aerial images of the mine, located in the Andes of Northern Chile, DSMs with a ground sample distance (GSD) of 14cm are created for calculating the volume of ore extraction. The accuracy is similar to terrestrial laser scanning (TLS), which has proven to be the best tool for surveying sites where access is limited due to safety constraints or harsh conditions. But the use of TLS is more costly and time consuming than UAS. Fixed wings are well suited to operating in windy areas where the air is full of dust and temperatures are low. With a wingspan of 96cm, the eBee can endure strong breezes and the rear-mounted propeller further improves safety. The foam frame results in a weight of just 700 grams, enabling it to be launched by hand and to stay in the air for 45 minutes. It automatically returns to the take-off point and lands autonomously if the battery level is low or the wind is too strong. The system comes with eMotion 2 flight planning and control software and Postflight Terra 3D-EB photogrammetric software, specially developed for eBee images.

MERGING

A lot of testing is still going on to obtain insight into how UAS can be an alternative to geodata collection techniques in use today. Franken (see page 23) investigated the aptness of a multicopter to replace airborne Lidar, which is the current method for mapping breakwaters along the North Sea coastline, since Lidar is costly for small project areas. The UAS survey resulted in a height accuracy of the DSM – density 100 points per m^2 – of 11mm. This article also shows another advance: merging of UAS data with other geodata. Here the DSM, created from UAS imagery, and bathymetric depths collected by a multibeam echosounder operated from a vessel have been merged to create one seamless DSM. On page 26 Fiermann and co-authors present a tandem system consisting of a copter and a ground robot for autonomous inspection to support surveillance staff, repair servicemen operating in harsh conditions and many others.

REMOTE AND HARSH

To demonstrate suitability in remote and harsh environments, researchers do not flinch at the thought of travelling to our planet's extremes. In a 2014 paper published in the *International Journal of Applied Earth Observation and Geoinformation* (27 Part A, 53-62), researchers from Tasmania report on capturing the micro-topography of moss beds in East Antarctica using a MikroKopter OktoKopter, payload 1.5kg, equipped with a Canon 550D digital SLR 18MP camera. Each of the 200 images, 1cm GSD and collected during one flight on 24 February 2011, covered an area of 64m by 43m. A total of 42 ground control points (GCPs) were measured with a Leica 1200 DGPS receiver, accuracy 2-4cm; 12 GCPs were used for georeferencing and 30 for accuracy assessment. Although the autopilot failed due to magnetic declination which forced manual piloting, a 2cm DSM and a 1cm orthomosaic of a one-hectare area could be created, both with 4cm accuracy. If unmanned aerial systems can operate successfully in the Andes and Antarctica, they can operate anywhere in the world – no matter how remote the environment and how harsh the conditions. However, legislation may still be a snag.

GIM INTERNATIONAL INTERVIEWS PETER COSYN

The Rapid Rise of UAS in Geomatics

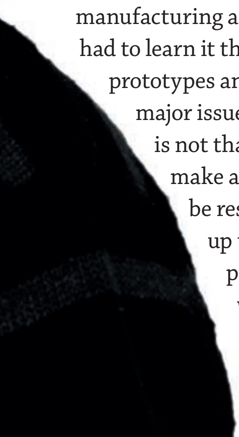
Peter Cosyn co-founded Gatewing in 2008. The start-up company's X100 fixed-wing UAS soon attracted interest from Trimble, who acquired the activities in 2012. In this interview with *GIM International*, Peter provides insights into the company's evolution and shares his thoughts on the future.

The Gatewing company was founded as a spin-off from your PhD research at Ghent University. How did you experience the transition from a scientific environment to running a company?

My PhD research involved micro air vehicle development and optimisation. Such vehicles are only about the size of a big smartphone, so the research did not have much in common with what we later did at Gatewing and it was a significant transition. Although the two other co-founders, Maarten Vandenbroucke and Maarten Van Speybroeck, came from a business environment, running a start-up was new for them too. I did benefit from my PhD experience though. For example, I had to apply for government funding for my PhD and post-doc, which meant I knew how to attract innovation funding. At the university, I had to work independently, think 'out of the box' and team up with others to explore UAV concepts as I could not rely on a 'UAV lab'. In general, starting the business was a real endeavour but we were eager to learn from business experts while trusting our ideas and our gut feeling about the market. We made a prototype and checked it with a few key accounts such as big mining companies. Then we just went for it and started developing the Gatewing X100.

What were the main hurdles to overcome in the design and operationalisation of the X100, and what are its distinguishing features compared to other fixed-wing UAS?

A big hurdle was the fact that we were no experts in autopilot or control design. I had experience in wing design, aerodynamics and propulsion. My colleague, Maarten Van Speybroeck, had the most experience in CAD and knew a lot about manufacturing and materials. We had to learn it the hard way, making prototypes and testing them. The major issue here was that a UAV is not that forgiving if you make a mistake. You need to be resilient when gathering up the broken pieces of a prototype you've been working on for days and that cost you a significant chunk of your limited funds! Today, with all the open-source platforms, making a UAV might seem straightforward. But making it reliable, industrialising its design and manufacturing, and ensuring compliance with FCC (Federal Communications Commission), CE and other norms actually involves following a long, arduous path.



The fact that we were not RC enthusiasts probably helped us develop a system intended for professionals who lacked 'piloting skills'. A distinguishing feature of the X100 compared with other (at that time typically bigger or rotary-type) UAS on the market was that it was completely autonomous from start to landing, with user interaction limited to simple commands (land, go home, etc). This reduced the barriers to entry for the commercial market. Manually assisted landing and pilot 'override' for take off, landing or emergency was still the norm when we started and it is still an aspect of many UAS.

When Trimble contacted us, we were at a first reluctant to give up our 'baby'

An additional distinguishing feature was the foam structure we used with internal composite reinforcements. We basically did the opposite of what was common for most (military) fixed-wing UAS. It gave us an advantage in production, plus resistance to shock and a significant improvement in safety. This looked important so we went for a patent.

The X100 is one of the few fixed-wing UAS on the market. What are its main strengths and weaknesses compared to rotary wings?

A fixed wing has an important advantage: it benefits from wing lift enabling it to fly efficiently at high speed, whereas a rotary UAV does not. This means that a fixed-wing UAV of comparable size and weight will be able to map a much bigger surface than a rotary UAV in a given amount of time. Knowing that size of the airframe impacts the acquisition and running costs of a UAV and also the risks (and regulations) involved, it is clear that fixed wings have an advantage for mapping. There is a trade-off and it depends on the size of the area covered. A Gatewing X100 or Trimble UX5 is a good match when you need to cover from tens of hectares up to tens of square kilometres. Meanwhile, if you just need to fly and map a building or a small field, a rotary UAV of the same scale might do just fine. Additionally, rotary UAS are a match when you need vertical surveying (e.g. of buildings) or you need to

Peter Cosyn

Dr Peter Cosyn is co-founder and R&D director of Gatewing, a company based in Ghent, Belgium, which was acquired by Trimble in 2012. He obtained a PhD in electromechanical engineering from Ghent University in 2006. He has 12 years' experience of developing unmanned aerial systems and is author of multiple international papers and a patent on the subject. He has been involved in multiple technical working groups and European Commission hearings to support the EU legislation process of UAS.

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take off and land in a very enclosed area. A disadvantage of a traditional fixed wing is that it needs significant space to land. The UX5 addresses this limitation with its steep take-off and landing capability.

Trimble acquired the company in early 2012. Why was this giant geomatics company interested, and what are the main advantages for yourself?
Trimble was probably the first multinational geomatics company that understood the power of combining the massive point clouds and geospatial data our solution provides with the geospatial data of optical and GNSS solutions Trimble provides to its customers. Trimble's move came as a bit of a surprise to us. We knew the geospatial giants of course – some of our dealers were Trimble or Topcon dealers – but we did not expect Trimble to be interested so early. We were a 3-year-old start-up that would normally go through a venture-capital funding stage to keep growing. A 'born global' company such as Gatewing with a new, complex hardware product needs a big team and significant investment to succeed. When Trimble contacted us, we were at a first reluctant to give up our 'baby'. Our uncertain funding options, the fact that Trimble would keep the organisation intact after acquisition and Trimble's expected, positive impact on our current and future products and sales were deciding factors. Trimble's professional dealer networks and its UAS-relevant vertical markets are an advantage for us.

What is the profile of your present consumer base?
Our main user is the surveyor focused on asset mapping who typically works for a service company or is an internal supplier of geospatial data for a big company. Additionally, we sell to mining companies and those involved in construction and engineering works. We also have clients in agriculture, forestry, energy, dredging, governments and a significant number of universities. Geographically we sell almost everywhere. However, our main focus is on countries with Trimble survey dealers – we have around 45 dealers today – and where we have airspace access. The latter limits our exposure at the moment; we don't have any dealers in the USA, for example, since the FAA (Federal Aviation Administration) does not currently allow commercial use.

How are training and services arranged?
We provide training to our dealers, who then train their customers, and training to customers who apply for it. A training course consists of a classroom session, two field days and an examination which you need to pass to become an approved pilot. It's not rocket science; the procedures are straightforward, but it's important to keep certain operational standards and safety aspects in mind and that is what we measure during the exam. Our training courses are recognised and our certificate is required by multiple Civil Aviation Authorities. Additionally, we provide training on our office software (Trimble Business Center) which has a photogrammetry module and delivers optimal accuracy. The Trimble Global Services team manages the support to our dealers and Gatewing manages second-line support. New service centres will be added in the coming months to further improve our customer service.

On which major developments are you working now?
I can't give you details, but the main theme is that we are working to increase flexibility in our planning and flight operations. This improves the workflow for different project types and also improves it for the challenging environments that customers face. We will tackle this with software updates and additional hardware options.

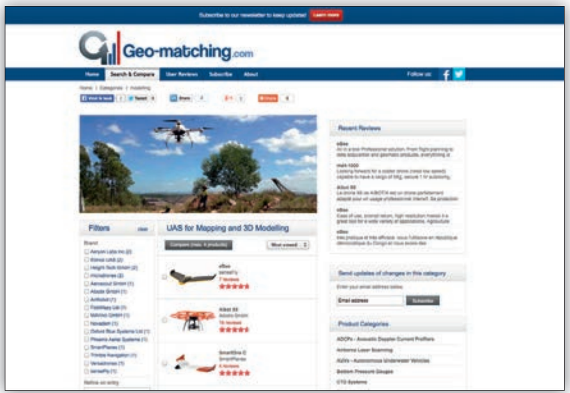
Another key element in our future roadmap is data accuracy, but our marketing communication needs fine-tuning first. We are leading the

field, but this is not well perceived by the market. For example, if you measure your assets at our minimal ground sample distance and you check the point cloud, you will see that we reach on average 2cm in Z and even better in XY. Sigma values have similar results. That's why we consider our solution 'survey-grade'. This quality depends on multiple elements of the solution, especially our data acquisition stability, image quality, camera stability and image processing algorithms. Low-cost solutions (and even some high-cost solutions) available on the market today will not provide you this accuracy and data consistency, which sometimes makes a significant difference. They might be well suited for a client with limited needs but we also see many people considering them for survey tasks. From a customer perspective, I understand the confusion: exciting flight demos (everybody likes a flying 'toy') and nice-looking 3D models captured in optimal conditions are persuasive, especially when combined with sometimes misleading datasheets. Unfortunately, the reality can be different and the market needs to realise this.

Furthermore, the UX5 UAS was released through Trimble's Agriculture distribution channel recently so we will see development that serves these clients as well. Point clouds and surface models play a role here but the image interpretation part will be the big driver in the future.

DETAILED PRODUCT INFORMATION ON GEO-MATCHING.COM

COMPARING UNMANNED AERIAL SYSTEMS



Have you recently decided to buy or use an Unmanned Aerial System (UAS) for your aerial surveys, but have no idea how to choose between all the different models available on the market? No time to search for and request their technical product specifications? Are you curious to know how fellow professionals experienced using your preferred model? Then visit Geo-matching.com.

Geo-matching.com is a product comparison website for devices used in geomatics, hydrography and related industries, featuring detailed spec-based comparisons and user reviews for more than 650 products. Geo-matching.com features many devices, including Unmanned Aerial Systems.

Unmanned Aerial Systems

The types of Unmanned Aerial Systems (UAS) that qualify for inclusion on Geo-matching are all those equipped with cameras, Lidar or other sensors capable of surveying Earth and/or sea surfaces, including the relevant processing software. The following systems are currently listed:

- Aeroscout (Scout B1-100 UAV)
- Aeryon Labs (Aeryon Scout, Aeryon SkyRanger)
- Aibotix (Aibot X6)
- AirRobot (AR180)
- Elimco UAS (E-300 Viewer, E-100 Micro)
- FotoMapy (EasyMap UAV)
- Height-Tech (HT-8-2000, HT-6-800)
- MAVinci (Sirius Pro)
- microdrones (md4-200, md4-1000)
- Novadem (U130)
- Oxford Blue Systems (Resolution)
- Phoenix Aerial Systems (Phoenix AL-2)
- senseFly (eBee)
- SmartPlanes (SmartOne C)
- Trimble Navigation (Trimble UX5)
- Versadrones (Versa X6)

The website details specifics relating to platforms, dimensions, the environment, on-board navigation sensors, imaging/scanning devices, launching and landing, piloting, associated software, automatically generated products, safety and base stations. These can be used to filter the range of products.

Geo-matching.com

Other geomatics products covered by Geo-matching.com are GNSS Receivers, Total Stations, Digital Aerial Cameras, Terrestrial Laser Scanners, Airborne Laser Scanning, HR Satellite Imagery, Photogrammetric Imagery Processing Software, Inertial Navigation Systems, Mobile GIS Systems, and Remote Sensing Image Processing Software.

Find Geo-matching.com at *www.geo-matching.com*.

One of the operational issues affecting UAS is legislation; most jurisdictions require permits and pilot licences. How do things stand presently, and what do you expect for the near future?
Legislation is a big issue at the moment but primarily because the rules of the game are not established, are incomplete or are very restrictive in many countries, including the USA. Proper legislation is essential to market growth. UAV airworthiness approvals, operator certificates and pilot licences are all needed in order to create accountability, reduce the risk of accidents in the air and on the ground, and allow insurance to capture the excess risk. Safety is the main driver and this also means that the legislation should be scaled to the risks involved. I was involved as an industry specialist in a few working groups on rules and regulations, and I know that it is a huge task to accomplish a well-balanced rule set. There is a 'chicken and egg' problem here because there is limited flight data available to validate the rules, but we first need rules in order to be able to fly...

I expect governments to address the easy part first: flights close to the operator with vehicles that have acceptable risk in case of failure. This is the approach of both the USA and EU. We will see the first harmonised rulemaking in 2015 leading to actual rules in the USA, EU countries and beyond shortly afterwards, and a gradual entry of more complex operations (with increased requirements for the UAV and pilot) probably resulting in a full merger of UAVs (big and small) and aircrafts in our airspace by 2030. For our scale and operations, the earlier date is more important than the later one but some applications might take a few more years before they become really marketable (e.g. long-range corridor mapping).

To what extent do you foresee that UAS will replace traditional survey methods?
At this moment we see that the main markets are created when timely access to the airspace is possible and where a significant market exists for mapping big and changing industrial or civil assets. I'm talking about emerging markets or developed regions with favourable rules (driven by their low population density) such as Canada, Australia or Scandinavia where vast areas need coverage. Because of the increasing data quality, the decreasing cost of ownership and especially the improvements in legislation, I do expect that the accessible market will gradually grow up to a point where every surveyor or professional that can benefit from mapping assets for themselves or for clients has access to the technology, whether in ownership, on loan or as a data client. In parallel, we will see a growing number of UAS applications that span the 'survey spectrum' from small-scale vertical mapping of infrastructure to large-scale mapping that competes with the traditional photogrammetry companies.
A powerful element of UAS mapping is the fact that it can gather data in an automatic, consistent way for later analysis in an office environment rather than in the field. UAS create a 'virtual scene': a snapshot of the state of the project or asset.

Still, there are limits and they will be mainly driven by the regulations. I expect that training and permits will remain a necessity for any professional device, regardless of its scale or price. Products that ship in a box without proper service and certificates or products that flirt with the B2C market could face a very strict regulatory burden because of the safety and privacy issues involved, and this will limit their market potential. So I believe that UAS will remain a tool for the professional who is committed enough to make the investment.

> *The market is undoubtedly huge, but there is also a lot of hype*

A lot of new companies are entering the UAV market. How do you see the UAS sector developing in the long run?
A UAV is a very 'cool' product and anybody who starts brainstorming will find an almost unlimited number of potential applications. This definitely fuels the sector in general. However, due to the regulatory burden there is a huge barrier for individual companies to test their business case and then, when proven, grow their business. At the same time, this artificial situation gives new start-ups the impression that the market is a 'free for all' and we see them popping up everywhere. The market is undoubtedly huge, but there is also a lot of hype. Proven applications, and I certainly consider our surveying solution to be one of them, will eventually emerge as the clear growth paths. But growing is not easy; an industrialised solution requires effort and investment. Therefore we will see many companies disappear as quickly as they appeared, we will see consolidation between those players who already have a footprint and we will see a few smaller players specialising in useful niche applications.
In the long run, the commercial UAV market is definitely a multi-billion-dollar business. The biggest part of the market, however, will not be selling UAS but rather selling the software and services that enhance the solution to address real customer needs. We will keep focusing on the solution rather than on the aircraft only. ◂

A PRODUCT SURVEY ON SYSTEMS AND FEATURES

UAS for Mapping

In recent years, unmanned aerial systems (UAS) have attracted tremendous attention from surveyors and other geodata collectors all around the world. Nowadays, UAS equipped with GNSS, IMU and RGB, NIR or TIR cameras and possibly Lidar have evolved into high-potential surveying devices which have now definitely passed the stage of 'toys for boys'. This article focuses on UAS for mapping and 3D modelling and provides a detailed survey in tabular format on the features of the prevailing systems, both fixed wings and multicopters, available on the market today.

Mathias Lemmens gained a PhD degree from Delft University of Technology, The Netherlands, where he presently lectures on geodata acquisition technologies and geodata quality on a part-time basis on the recently renewed geomatics MSc programme. He is the author of the book *Geo-information: Technologies, Applications and the Environment* published by Springer in 2011. He was editor-in-chief of *GIM International* for ten years and now contributes as senior editor.

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An unmanned aerial system (UAS) is an aircraft which flies without a human pilot on board. It is steered wirelessly by remote control or flies on its own following a pre-specified air path guided by a global navigation satellite system (GNSS) and an inertial measurement unit (IMU). In this case, it is continuously monitored by a human operator who can intervene if necessary, such as when the UAS should encounter heavy turbulence or face unforeseen obstacles. UAS come in wide diversity of shapes, sizes and grades; they may be as large as aeroplanes or small enough to fit into the palm of your hand. They may serve a wide variety of uses ranging from reconnaissance and bombardments of enemy targets to more peaceful practices such as parcel delivery services and inspection of flooded areas. Originally designed for military use, today's UAS have proven their aptness for mapping hazard-prone areas, monitoring flooded areas, cadastral mapping, inspecting pavements, and many more non-violent geo-related tasks.

POPULARITY

Notably, no geodata-collection technology has become so popular among so many surveyors and photogrammetrists in such a short time as UAS. What these professionals value most is the ease with which sites can be revisited. The same area can be flown on a quarterly, monthly or even weekly basis, which is ideal for rapid and frequent monitoring of dikes, dunes, landslides, construction sites, open-pit mines, crops, floods and many other sites. Some field surveyors have to operate in quarries and mines, walking over piles of hazardous waste or placing their rods while surrounded by roaring heavy machinery. A UAS relieves them from visiting such sites in person, thus avoiding potential accidents and health risks. Purchasing costs are low and the piloting and operation of a UAS can be learned within a couple of hours to a few days. The accuracy of the orthomosaics, digital elevation models (DEMs), maps and 3D city and landscape models obtained from a UAS is similar to conventional land surveying and photogrammetry.

Brand	eBee	E-300 Viewer	EasyMap	Resolution	Sirius Pro	SmartOne C	Trimble UX5
Platform							
Year of introduction / last update	/ 13	10 / 14	12 / 13	05 / 13	/ 13	/ 13	13 / 13
Max. payload [kg]	0.15	4	0.35	2.3	1.1	0.4	0.5
Max. stay in air [min]	45	165	45	135	50	50	50
Max. speed [km/h]	90	120	90	120	80	90	140
Max. height [km]	1	5	1	0.75	1.8	1	0.75
Span width [cm]	96	480	90	234	163	120	100
Height [cm]	11	40		27	21	10	10
Empty weight [kg]	0.4	15	1.4	3.5	2	0.8	2.5
Transportable on human back	Y	N	Y	Y	Y	Y	Y
Environment							
Operation temp. range [ºC]	-15 / 40	/ 50	-15 / 40	-10 / 40	-20 / 45	-20 / 40	-20 / 48
Max. wind speed [m/sec]	12	12	15	14	18	13	18
Imaging/scanning devices							
Camera	Y	Y	Y	Y	Y	Y	Y
Lidar	N	N	N	N	N	N	N
Built-in stabilisation	N	Y	N	Y	N	N	Y
Exchangeable	Y	Y	Y	Y	Y	Y	Y
Sensor tilting for oblique views	N	Y	N	N	N	Y	N
Launch and landing							
Min. Ø launch / landing site [m]	25		25	1	100	20	20
Launching method	H	C	H	H & C	H	H	C
Automatic landing	Y	Y	Y	Y	Y	Y	Y
Fully pre-programmable flight	Y	Y	Y	Y	Y	Y	Y
Piloting & safety							
Min. size of field crew	1	1	1	1	1	1	1
Piloting skills required	N	N		N	N	N	N
Training provided [hrs]	1	40	16	N	27	4	15
Collision avoidance system (CAS)	Y	Y	N	N	N	N	N
Autonomous emergency landing	Y	Y	Y	Y	Y	Y	Y
Ground base station							
Sensor control	Y	Y	Y	Y	Y	Y	Y
Real-time image/video downlink	N	Y	N	Y	N	N	N

▲ *Table 1, Main features of fixed-wing UAS; H: launch by hand; C: launch by catapult.*

BACKBONE

The rapid rise and growing popularity of the UAS ensued from a once-in-a-decade convergence of developments. Micro-electronics, auto-piloting, high-charge batteries, super materials that are strong yet lightweight, wireless communication, compact digital cameras, image-processing software, miniaturisation of GNSS and inertial navigation systems (INS), and so on – all of these novelties created synergy. However, the key to the success of UAS lies not only in the hardware and electronics but also in the ability of today's software to automatically derive orthoimages and DEMs from overlapping digital images and airborne Lidar point clouds. The scientific fields of computer vision and artificial intelligence have definitely contributed to the development of the backbone of UAS through fundamental research. Indeed, today's photogrammetric software supports high automation of the entire chain, from flight planning, self-calibration of consumer-grade cameras and aero-triangulation through automatic block adjustment up to the creation of DEMs and orthomosaics as well as their confluence: 3D city models and 3D virtual landscapes in which a surveyor can place a cursor, as if it were a rod, over a terrain point from the comfort of an office. Field survey is only necessary when high-precision georeferencing is required, and this is done by measuring through ▶

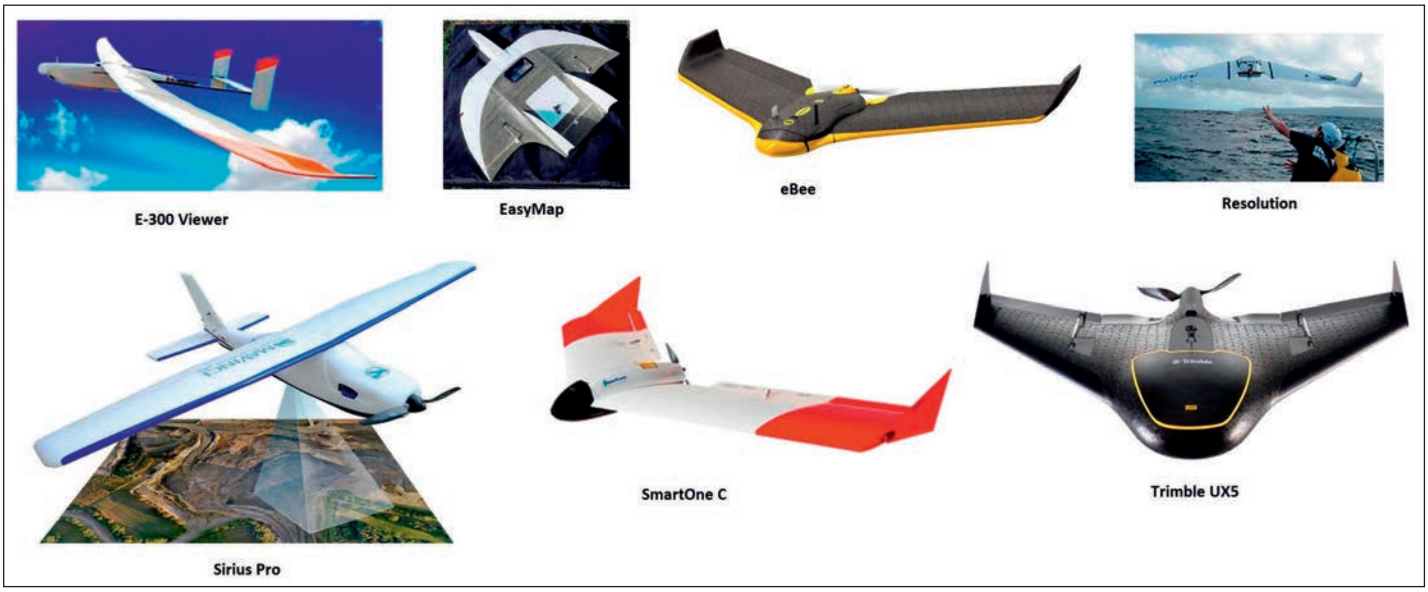

Figure 1, Fixed wings included in the product survey listed in Table 1.

differential GNSS the coordinates at sub-centimetre level of around half a dozen ground control points (GCPs) evenly distributed along the borders of the area. As a result, the full survey, from flight planning up to the final georeferenced products, can be conducted in just one or two days.

APPLICATION EXAMPLES

Technische Universität München demonstrated that a Falcon 8 – an octocopter (eight rotors), designed in a cut V shape – from Ascending Technologies (AscTec) equipped with a Panasonic DMC Lumix LX3 digital camera is suited to study the movements of pedestrians when they form a group in an urban area. At a flying height of 85m, images where recorded with a GSD of 1.5cm covering a ground area of 48 x 27m; pedestrians covered an image area of 30 x 45 pixels. Stability is ensured by software allowing rapid feedback from sensors to rotors. This UAS remains stable up to wind speeds of 10m/sec (5 Beaufort; fresh breeze), can carry a payload of 750g (maximum take off: 2.2kg) and can stay in the air for 20 minutes. Navigation and positioning is done with GNSS, IMU, a barometric height sensor and a compass. The Panasonic LX-3 is a compact camera with a focal length of 5.1mm, an image size of 3648 x 2736 pixels and a pixel size of 2µm. The complete system including camera, mobile ground station, batteries, charger and transport case can be obtained for less than EUR20,000. The same system was used by the City of Winterthur, Germany, to evaluate its suitability for cadastral mapping using orthoimagery generated from images captured by the UAS. Also the Dutch Kadaster tested the fitness for use of this UAS for cadastral purposes, more specifically for property boundary identification in urban areas. In addition to the Falcon 8, the Microdrone MD-4 1000 Beta was also tested. This UAS is a quadrocopter (four rotors), can carry a payload up to 1.2 kg and can stay in the air for nearly 1.5 hours. The camera on board was an Olympus E-P3 OGT with a focal length of 17mm, an image size of 4032 x 3024 pixels and a pixel size of 4.4µm. The manufacturer claims that even inexperienced people can learn to operate the UAS with just one hour of training. The product is intended for not only surveyors and other geodata collectors but also the police, firefighters, estate agents, TV producers and movie makers, farmers, architects and many more.

The uplift capability of wings reduces energy consumption and enables high-speed flying

CATEGORISATION

UAS platforms can be split up into two broad categories: fixed wings and multicopters. Most of these platforms are lightweight and thus easily portable on a human back. A fixed wing can use the uplift capability of its wings, which reduces energy consumption and enables high-speed flying. Hence, a fixed wing can stay in the air longer than a copter, can resist higher wind forces and capture larger areas per flight. A fixed wing is thus better suited for mapping large areas than a copter of comparable size. On the other hand copters are more manoeuvrable and need, in contrast to fixed wings, only small launch and landing spaces as they can take off and land vertically (VTOL). Therefore,

Brand	Aeryon Scout	Aeryon Skyranger	Aibot X6	AR180	HT-8-2000	md4-1000	Phoenix AL-2	Scout B1-100	U130	Versa X6
Platform										
Year of introduction / last update	09 /12	13 / 13	11 / 13	/ 13	11 / 13	08 / 13	12 / 13	12 / 13	06 / 13	11 / 13
Max. payload [kg]	0.4	1	2.5	1.5	2	1.2	4	30	0.8	2
Max. stay in air [min]	25	50	30	35	20	88	15	60	20	25
Max. speed [km/h]	50	65	60	50	70	54	60	50	45	35
Max. height [km]	0.5	1.5	2		0.5	1	2	0.2	2.2	1.5
Propulsion	B	B	B	B	B	B	B	F	B	B
Ø [cm]	72	102	105	193	90	173	110	320	130	90
Height [cm]	20	24	45	40	45	50	45	100	20	35
Empty weight [kg]	1.4	2.4	2.5	2.5	2.3	2.65	8	45	1.7	3
Number of rotors	4	4	6	4	8	4	8	1	4	6
Transportable on human back	Y	Y	Y	Y	Y	N	Y	N	Y	Y
Environment										
Operation temp. range [ºC]	-30 / 50	-30 / 50	-20 / 40	-20 / 50	-10 / 35		-20 / 40	-10 / 40	-10 / 35	-5 / 60
Max. wind speed [m/sec]	14	65	12	10	15			10	12	8
Imaging / scanning devices										
Camera	Y	Y	Y	Y	Y	Y	Y	Y	Y	
Lidar	N	N	Y	N		Y		Y		
Built-in stabilisation	Y	Y	Y	Y	Y	Y		N	Y	Y
Exchangeable	Y	Y	Y	Y	Y	Y		N	Y	Y
Sensor tilting for oblique views	Y	Y	Y	Y	Y	Y		N	Y	Y
Launch and landing										
Min. Ø of launch / landing site [m]	5	6	2	5	3	1	2	10	2	2
Automatic landing	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
Fully pre-programmable flight	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Piloting & safety										
Min. size of field crew	1	1	1	1	1		2	2	1	1
Piloting skills required	N	N	N	N	N		N	N	N	N
Training provided [hrs]	Y	Y	3	24	10	8	48	24	7	16
Shielded propellers	NA	NA	Y	N	Y		Y	N	Y	N
Collision avoidance system	N	N	Y	N	N		Y	N	Y	N
Autonomous emergency landing	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Ground base station										
Sensor control	Y	Y	Y		Y			Y	Y	Y
Real-time image / video downlink	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

▲ *Table 2, Main features of multicopter UAS.*

a copter is ideal for mapping buildings and small areas.

PRODUCT SURVEY

The backbone of this article is a survey on the features of the diverse fixed-wing and multicopter UAS available on the market today. Tables 1 and 2 list the main features of fixed-wing UAS and multicopters, respectively. Figure 1 depicts the fixed wings and Figure 2 the copters included in our product survey. The information has been provided by the vendors themselves by filling in a questionnaire prepared by the author through product comparison website Geo-matching.com. The listing is not entirely complete. For example, the Falcon 8 from Ascending Technologies, mentioned above, is not present in the list. We hope that this article will encourage more vendors to upload the specifications of their UAS products onto Geo-matching.com. All lightweight UAS in the survey as tabulated are propelled by an electric motor, powered by a battery. The service life of the battery together with wind ▶

▲ *Figure 2, Multicopters included in the product survey listed in Table 2.*

Service life of battery together with wind speed determines how long the UAS can stay airborne

speed largely determines how long the UAS can stay airborne. All fixed wings listed are propelled by an electric engine. In the overview, shown in Table 2, only one copter, the Scout B1-100 – empty weight 45kg and able to carry a payload up to 30kg – is propelled by a combustion engine. For nearly all systems the main sensor on board is an HD RGB camera. The camera mounted on a UAS is usually consumer-grade or used by professional photographers and manufactured by Sony, Olympus, Panasonic, Canon or other major producers. All systems are equipped with GNSS and IMU for navigation purposes and for calculating position and orientation of the camera during exposure in the block adjustment procedure. Some extend these sensors with barometers and compasses. Although flight planning software is standard, photogrammetric and point cloud processing software is usually not a standard part of the purchase. This is also true for the ground computers; some provide a notebook or tablet equipped with control software but others do not, which enables clients to choose a suitable computer themselves. Installation of other sensors, such as near infrared, thermal infrared and hyperspectral cameras, is often optional. Photogrammetric and point cloud processing software recommended or delivered by the UAS vendors includes: Agisoft PhotoScan, Pix4D, Postflight Terra 3D EB and SmartPlanes Aerial Mapper. A lightweight UAS is rarely equipped with airborne Lidar as these devices are rather heavy and bulky compared to today's digital cameras.

HEAVYWEIGHT

A UAS used for mapping, reconnaissance and inspection is usually lightweight. However, there is always one exception that proves the rule, and in this case the exception is the Camcopter S-100, a rotorcraft from the Austrian company Schiebel. With a weight of 110kg, wingspan of 3.40m, a top speed of 222km/h, a ceiling of 5,500m and payload capacity of 50kg, this UAS is a mastodon compared to the others in use for geodata collection. It went into serial production in 2005, and more than 150 systems are in operation worldwide today. Powered by a 55hp Diamond engine, the UAS can stay in the air for 6 hours and serve a wide diversity of applications as the payload may consist of a variety of sensors including optical, near-infrared and thermal infrared cameras, synthetic aperture radar (SAR), ground-penetrating and maritime radar, and Lidar. No standard payload is offered; payload is integrated according to client needs. For example, the UAS has been equipped with a Riegl hydrographic Lidar designed to survey beds of water bodies in support of mapping coastlines, lakesides and riverbanks. But the Camcopter S-100 has also been used for power line surveillance and security monitoring during major events such as the 2010 G20 Seoul Summit. It is obvious that this system is one to two orders of magnitude more expensive than a lightweight UAS. With an empty weight of 45kg and a payload capacity of 30kg, the Scout B1-100, offered by the Swiss company Aeroscout, is another mastodon among the copters (see Table 1). In addition to a camera, this UAS is equipped with a Riegl airborne Lidar system. ◀

UAS Technology in Focus

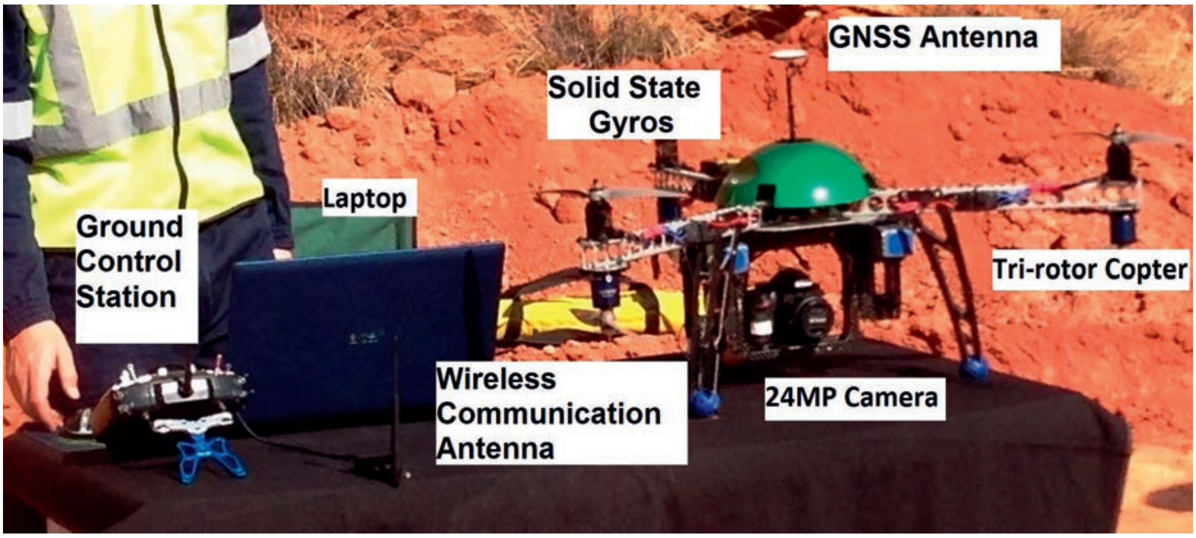

Figure 1, Components of a UAS; the tri-rotor copter shown has two propellers for each rotor.

A UAS intended for mapping, inspection or reconnaissance consists of a mix of elements including aircraft, a ground control station (GCS), on-board navigation sensors, a radio link for manual control of the aircraft, one or more geodata collection sensors and a wireless link for transmitting the data recorded by the geodata collection and navigation sensors to the GCS and PC, laptop or tablet (Figure 1). Usually the aircraft – whether a fixed wing or rotary wing – will be propelled by a battery-powered electric engine. However, the depletion of the battery charge is usually counted in minutes rather than hours. As a result, an aerial survey lasting one day may require a series of batteries of which the compound weight exceeds the total weight of the other parts of the UAS. Nevertheless, today's batteries may be powerful enough to allow a payload which is heavier than the aircraft itself. For mapping and inspection purposes, the on-board sensor will be a high-resolution RGB camera, a Lidar system, a near-infrared or thermal-infrared camera, a video recorder or a combination of these sensors.

Today's batteries may be powerful enough for a payload which is heavier than the aircraft itself

PILOTING

Since no human operator is on board, the aircraft has to be controlled by remote piloting using a radio link or (semi-) autonomously. Remotely piloted vehicles (RPVs) require continuous input from a human operator on the ground, who has a wireless connection to the UAS through the GCS. The images or videos captured by the on-board camera are transmitted to the computer through a real-time data downlink so that the operator on the ground may have a pilot's-eye view as if from inside the cockpit. Today, a UAS is usually controlled by a single person and can operate semi-autonomously, sometimes even up to the level of automatic take off and landing. The operator only intervenes when the UAS encounters an obstacle or other potential threat. The camera or other geodata collection sensors may be mounted such that they look nadir or may be attached to a tray which can revolve around one, two or three perpendicular axes so that the surface can be observed from a variety of angles. In order to preserve a fixed viewing angle under aircraft weltering, the mount may be equipped with an in-built stabilisation facility. Viewing angle, image exposure, zoom and other operating parameters of the sensor will be controlled by the pre-loaded flight plan, but the human operator may intervene through the GCS if necessary.

EYE CONTACT

The trend is towards more autonomous systems. Autonomous guidance means that the on-board computer fed by sensor inputs is in full control, rather than a human operator. While fully autonomous guidance is currently used for military operations, the control of a human operator remains essential for civilian use. In theory an autonomous flight requires no human input after take off, but in practice the operator will maintain eye contact with the aircraft during the entire flight. The use of a flight guidance system is now common, allowing semi-autonomous flights. Once airborne the UAS will be steered by an autopilot using the pre-loaded flight plan; in other words, the aircraft follows a set of pre-programmed waypoints. The core sensors enabling auto-piloting are small GNSS receivers and solid-state gyros, possibly accompanied by a barometer to measure height above ground and a compass to measure heading of the aircraft.

EXPECT THE UNEXPECTED

Unexpected situations can always arise, such as a sudden heavy wind, running out of power or facing a close encounter with another (flying) object; therefore, sensors should be able to detect the unexpected in order to avoid collisions or crashes. Many systems are not only able to detect the unexpected but also able to determine the correct course of action, such as manoeuvring the aircraft back to the take-off site, identifying a suitable place to land or – in the extreme case – arranging a soft crash which may result in damage to the UAS but avoids injuries to humans and animals, thus potentially saving lives. A semi-autonomous UAS is also able to monitor and assess its own 'health', status and configuration within its programmed limits. Hence, on-board sensors may detect a defective motor or damaged propeller of a multicopter and adjust the other rotors to compensate for the defects to ensure that the UAS remains stable in the air and thus under control.

DETERMINING VOLUME CHANGES OF THE CHUQUICAMATA OPEN-PIT MINE

UAS in the Andes

In mining, the determination of volume changes over time is an important surveying task. However, harsh environments can make gathering precise and up-to-date geodata challenging. Traditional land surveying and terrestrial laser scanning are faced with many hurdles when used in remote open-pit mines. UAS provides an alternative without compromising accuracy. Here, the authors present UAS surveys carried out high in the Andes.

The gathering of information in open-pit mines is associated with many risks. If security protocols are not strictly followed, heavy equipment may injure surveyors operating on site. In addition, digging ore produces dust, noise and other unfavourable working conditions. When located in mountainous areas temperature may be well below zero. Access is often limited due to safety regulations, or even impossible due to the harsh environment. Terrestrial laser scanning (TLS) is a proven tool under such conditions but requires substantial investment and logistics as well as many set-up points to avoid blind spots. A UAS allows regular aerial surveys to be conducted without blind spots. Also, there is no need for access to the pit as a UAS can be remotely piloted, while the efficiency and timelines of a photogrammetric workflow can be fully exploited.

CHUQUICAMATA MINE

Chuquicamata, Northern Chile, is the biggest open-pit copper mine by excavated volume in the world, and at 1,000m from top to bottom it ranks second in terms of depth (Figure 1). The diameter is 4km. Particularly, the depth level between 200 and 400m is being explored at present and thus has to be surveyed regularly. The pit lies at 2,800m above sea level; wind speed and direction may change rapidly which precludes replication of flight plans, while turbulences can cause air drops of several metres which requires the endurance of a fixed wing. The high altitude raises energy consumption and thus reduces flight time, while safe landing zones are rare. Since landing places may be small and rough, lightweight fixed wings are preferred in order to prevent damage to aircraft. To preserve a constant ground sample distance (GSD) the height above ground has to be upheld, which further defies flight planning.

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Olivier Küng has a background in computer vision and, together with fellow scientist Dr Christoph Strecha, he co-founded Pix4D in 2011. The company specialises in software for creating 3D landscapes from images taken with small-format / consumer cameras, and this is already being used by hundreds of organisations.

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The wind also causes dust to blow around which obstructs sight and thus contaminates the measurements, while digging may destroy ground control points (GCPs). However, experiences gained during numerous flights have given an understanding of where and when wind and dust are most severe, and this helps when defining the flight variables.

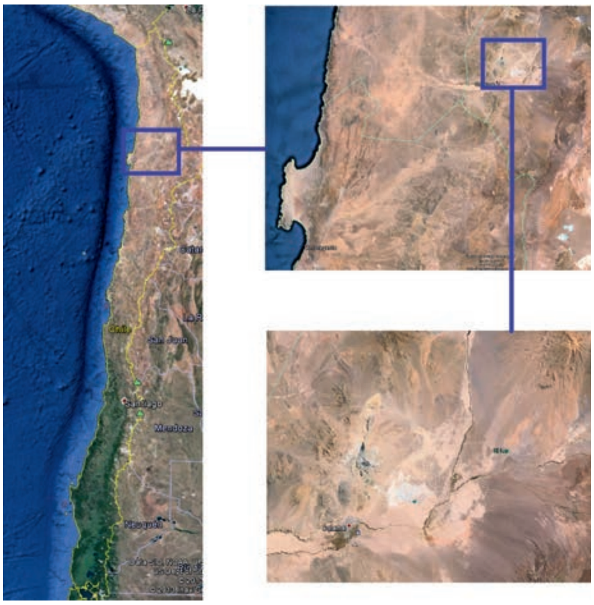

Figure 1, Location of the Chuquicamata mine in Chile.

VOLUME EXTRACTION

The UAS used was a senseFly eBee fixed wing, equipped with GPS / IMU and a 16MP Canon Ixus 125HS camera. During two months, weekly flights were conducted under equal circumstances. From the eight datasets, digital surface models (DSMs) were generated and volumes calculated. The features of the first dataset are presented here. The 266 images were acquired from a height of 250 metres with a GSD of 14cm. The images were processed with Pix4Dmapper within 1.5 hours on a standard desktop PC (a detailed description of Pix4Dmapper can be found in *GIM International*'s previous UAS special, published in 2013). Over 758,000 key points were automatically extracted, of which 263,000 3D points were generated for use in the bundle block adjustment (BBA), achieving a mean error of 0.16 pixel. Five GCPs were used for georeferencing purposes and two as check points. The height accuracy (1-sigma) was revealed to be 15cm which is consistent with the theoretical limit of 3 times the GSD. To create a DSM, all pixels were used resulting in 4 million height points. They were stored in a true-colour LAS format and automatically filtered and interpolated to generate a DSM with a GSD of 14cm. Figure 2 shows a sequence of DSMs and Figure 3 shows the volume change.

COMPARISON

Before the use of UAS, volume changes were computed from DSMs generated by TLS. Comparison shows that the volume computed from UAS imagery differs by less than 1% from the TLS volume. Hence, the accuracy of UAS is similar to TLS while UAS is safer, more efficient and more productive. Added to this, the orthomosaic created from the imagery and DSM can be draped over the DSM and this 3D digital landscape allows progress to be monitored and potential issues to be identified. Table 1 shows a UAS versus TLS workflow comparison when using two scanners.

The 3D digital landscape allows progress to be monitored and potential issues to be identified

OTHER EXPERIENCES

A flight over a 3.4km^2 discharge area of a mine tailing dam, located in the Atacama Desert in northern Chile, revealed that perpendicular flight lines, resulting in an overlap of over 85%, were necessary to prevent reflecting water bodies from hampering automatic processing.

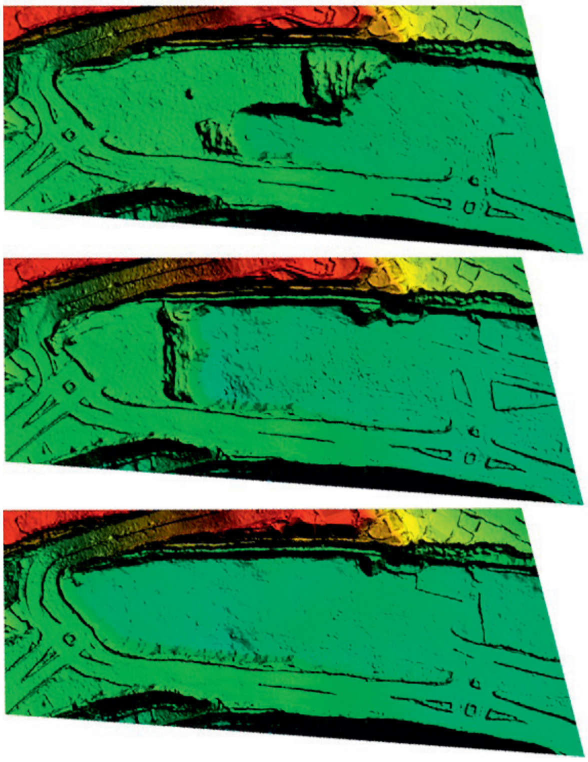

Figure 2, Time series of three DSMs at two-week intervals.

	TLS	UAS
Point density [pnt / m^2]	4	100
Operators	4	2
Vehicles	2	1
Need to access pit	Yes	No
Time on site	2 days	6 flights in 4 hours
Blind spots	Yes, depending on topography	No, because of vertical view and overlap
DEM generation	Extrapolation needed	Only measurements used
Availability of data	3-4 days	24-48 hours
Traceability of data	No	DSM and DTM allow traceability and comparisons

Table 1, Comparison between terrestrial laser scanning (2 scanners) and UAS.

The area was captured within 45 minutes; from the images with a GSD of 10cm, a dense DSM and accurate contour lines were generated. They provide indicators where soil and rock have slipped into the lake, which may cause flooding threats. Conducting height measurements for creating a DSM of a 7.5km^2 valley with height differences of 900m deep in the Andes can take 7 surveyors up to 10 days. Using UAS it took one day to install and measure 8 GCPs and one day to conduct 5 flights resulting in 1,290 images. Matching 12 million key points to generate 5 million tie points for BBA and next producing 50 million height points, both with Pix4D, took 12 hours on a standard Windows PC, resulting in a DSM and orthomosaic both with a GSD of 8.7cm.

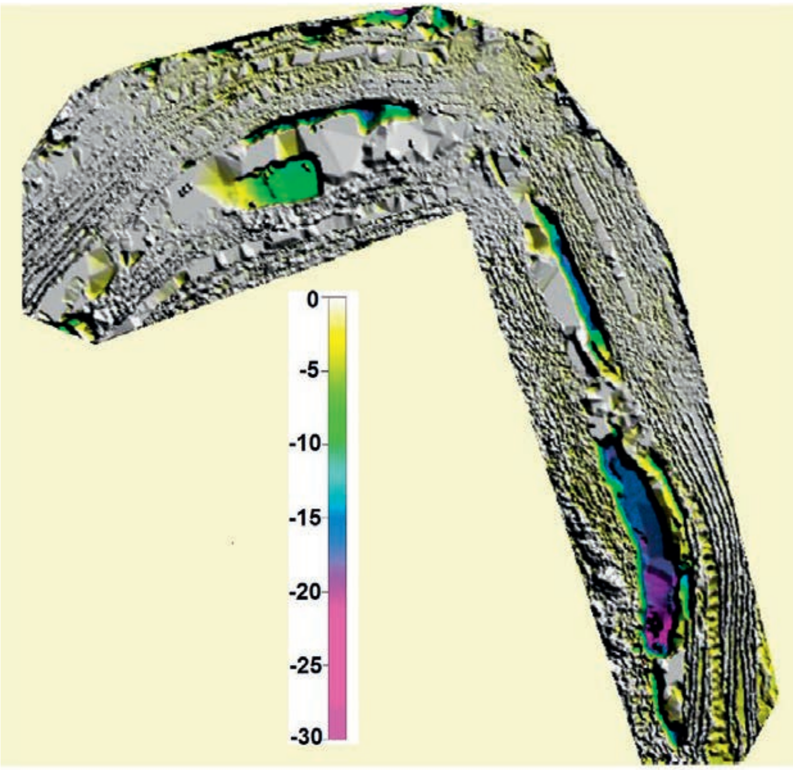

Figure 3, Copper ore extracted during one month (scale bar in metres).

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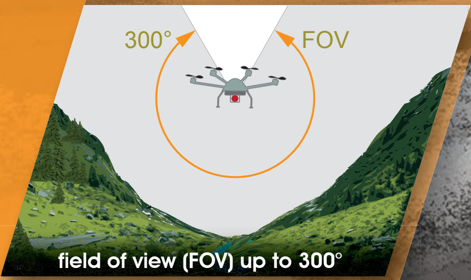

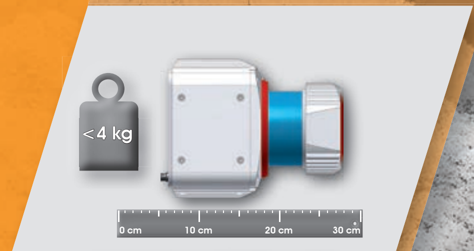

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MERGING UAS DEM AND BATHYMETRIC DEPTHS TO MONITOR BREAKWATER SUBSIDENCE AND EROSION

UAS at the Beach

The North Sea Canal connects the Port of Amsterdam with the sea. The two breakwaters at the mouth in IJmuiden are usually monitored on displacement of basalt block by airborne Lidar and on subsidence by annual levelling of permanent points. Could a camera-equipped UAS survey conducted simultaneously with a bathymetric survey provide information of equivalent accuracy? Here, the author shows that it could. Time series of 3D models of the breakwaters are useful for erosion and subsidence monitoring.

Monitoring of the breakwaters in IJmuiden, The Netherlands, is currently carried out using airborne Lidar together with spirit level / total station measurements. Airborne Lidar is excellent but very expensive when projects are small such as a breakwater survey. A UAS survey is a proper, and much more affordable, alternative.

GCPS AND CHECK POINTS

Prior to the actual UAS survey, conducted in August 2013, 20 circular disks with a diameter of 35cm were placed as ground control points (GCPs) regularly distributed over a distance of 1,000 metres along the breakwater and measured with RTK GPS. GCPs are indispensable since onboard GPS only picks up the L1 signal and the IMU provides orientation at an accuracy of just one degree. Although sufficient for conducting a flight autonomously when a flight plan is uploaded, the use of the GPS / IMU alone is not accurate enough to create high-quality digital elevation models (DEMs). The GCPs were measured with a 72-channel Novatel Frog GPS that uses commercial correction signals from the '06-GPS' network with an accuracy of 2cm in X and Y and 3cm in height. To assess the quality of the final DEM the 35 permanent points, which are measured yearly with total stations and levels to monitor subsidence of the breakwater, were also measured with RTK GPS.

UAS AND BATHYMETRIC SURVEY

After laying out the GCPs, the UAS survey was conducted with 80% along and across track overlap at low tide to ensure sufficient overlap with a multibeam echosounder dataset simultaneously collected at high tide. The overlap enabled mutual checks of both datasets. The UAS used, a Microdrone MD4-1000 equipped with a 24MP Sony NEX7, can stay airborne for 45 minutes (Figure 1). Three parallel flight lines at a height of 50 metres resulted in 433 images. After flight the camera was calibrated using specialised software and the values were used in the bundle block adjustment. Image matching resulted in the identification of around 4,000 tie points per image and a DEM with nearly 100 points per m^2 on average (Figure 2). A seamless orthomosaic with a ground sample distance (GSD) of 2cm was created from the DEM. The vessel used for the

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▲ *Figure 1, MD4-1000 operating above the breakwater in IJmuiden.*

bathymetric survey was equipped with RTK GPS, a motion sensor, a probe to measure the speed of sound in water and an ultra high-resolution R2Sonic 2024 multibeam echosounder. The survey was carried out by the Amsterdam-based company Deep BV at high tide to ensure the maximal overlap between UAS heights and bathymetric depths. The latter were resampled to a grid cell size of 10cm.

ACCURACY ASSESSMENT

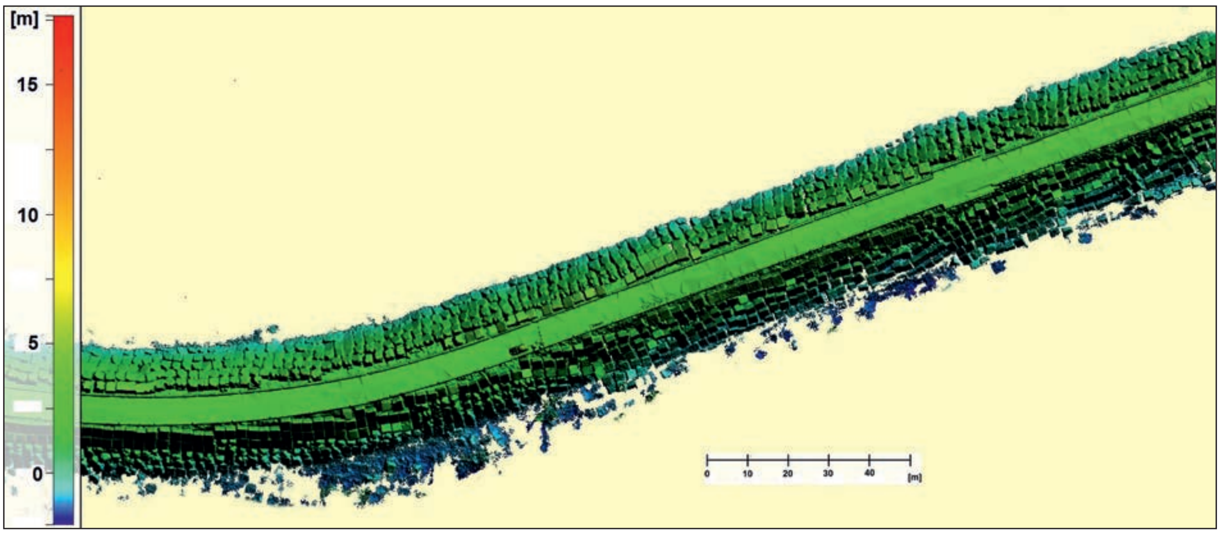
After integration of the UAS DEM and the bathymetric depths, the two datasets showed high resemblance so that a seamless DEM could be created (Figure 3). The 35 check points revealed a planar accuracy of 14mm and a height accuracy of 13mm. A further check using levelling and total station data supplied by the Ministry of Infrastructure and the Environment showed a height accuracy of 11mm (Table 1).

LEGISLATION

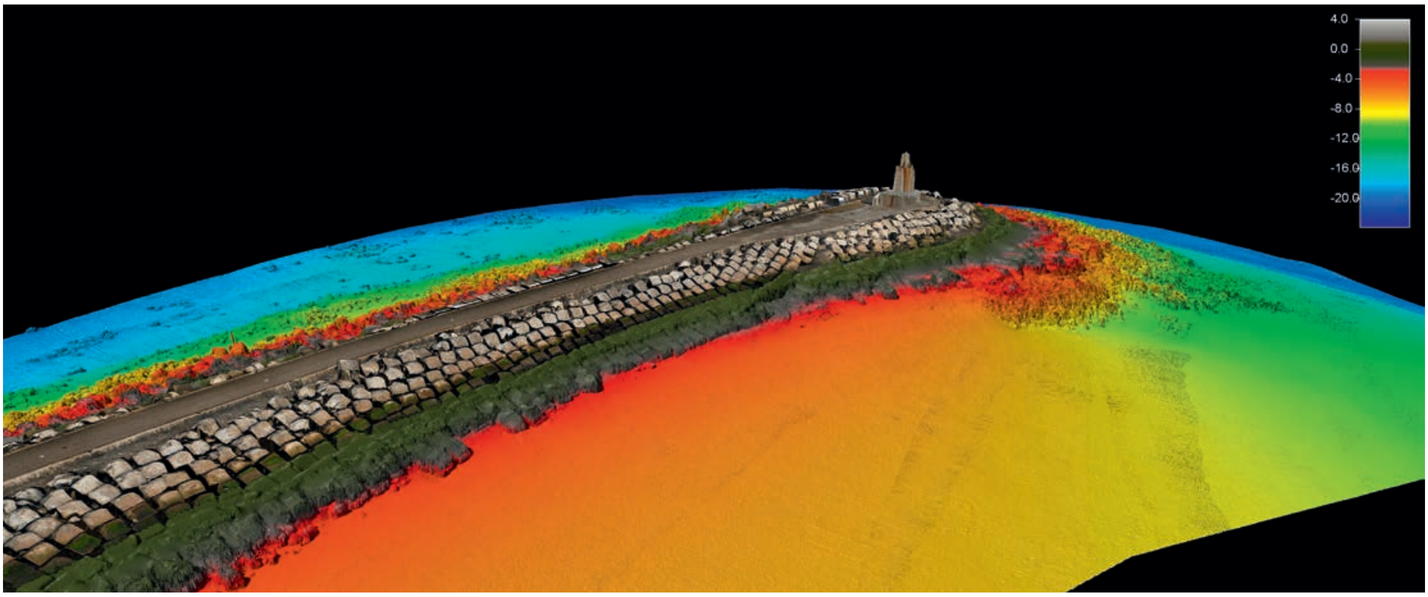
In The Netherlands, commercial UAS operation requires a permit from the Ministry of Infrastructure and the Environment. Permits are given to individual projects or to companies and Skeye is the first and, at present, the only UAS operator with a permanent company permit. To obtain this status all aircraft were checked on airworthiness, had to be insured for third-party liability and had to be registered in the National Aircraft Registry. Added to this, the pilots have to be BNUC-S licensed and operate according to the rules of the UK and NL Civil Aviation Authorities. However, a permit does not warrant operation everywhere at any time, since other airspace users have to be notified and provincial authorities require permission for take-off and landing outside an airfield.

▸ *Table 1, Accuracy assessment using GPS RTK and levelling/total station check points.*

	GPS RTK check points			Leveling / total station check points		
	Easting [mm]	Northing [mm]	Elevation [mm]	Easting [mm]	Northing [mm]	Elevation [mm]
Average of absolute differences	14	13	13	18	11	11
Standard deviation	12	11	7	13	8	10



▸ *Figure 2, UAS DEM of the breakwater.*



CONCLUDING REMARKS

UAS can achieve accuracies up to the centimetre level, which is higher than expected as the GCPs were measured with an accuracy of 2 to 3cm. Measuring the GCPs with higher accuracy may reveal even better results.

Figure 3. DEM generated from combining bathymetric depths and UAS heights.

SAFE NAVIGATION FOR AUTONOMOUS ROBOT SYSTEMS

Robots in Surveillance

Unmanned airborne systems operating in tandem with ground-based mobile platforms to capture an area autonomously support and improve the work of surveillance staff, repair servicemen operating in hazardous environments and many others. Yet, such systems are not widely used in civilian applications due to cost and complexity. The authors developed an unmanned ground system which – using GNSS and other positioning devices – accurately follows a pre-specified path while avoiding obstacles. Tests show that the prototype is user-friendly, safe and easy to operate.

The German SiNafaR project ('Safe Navigation for Autonomous Robot Platforms') was aimed at developing high navigation accuracy of robotic surveillance systems and their user-friendly, safe and easy operation [1]. In the project, which ran from late 2010 to January 2013 as a co-operation between Fraunhofer IIS, University of Würzburg, Zentrum für Telematik, EADS Deutschland and Wilkon, laser scanners, cameras, GNSS, INS and other navigation tools were mounted on a copter and on a four-wheeled vehicle. Combined with own software developed during the project, it was possible to achieve high accuracy both for the unmanned airborne system (UAS) and mobile unmanned ground system (UGS).

UAS AND UGS

The autonomous mobile robotic systems used within the project operate from the air and from the ground. A UAS can move quickly through the air, generates bird's-eye view images and images parallel to the terrain, and its operation benefits from the absence of obstacles at higher altitudes. But a UAS can

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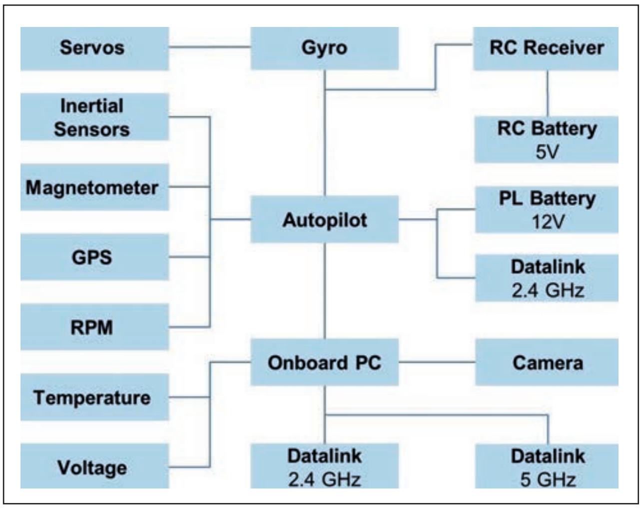
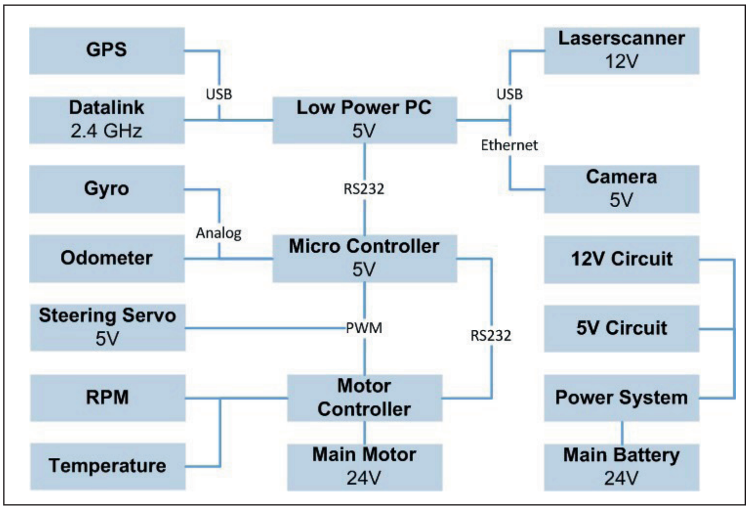


▲ *Figure 1, Schematic overview of the hardware components of the UAS.*



▲ *Figure 2, Schematic overview of the hardware components of the UGS.*

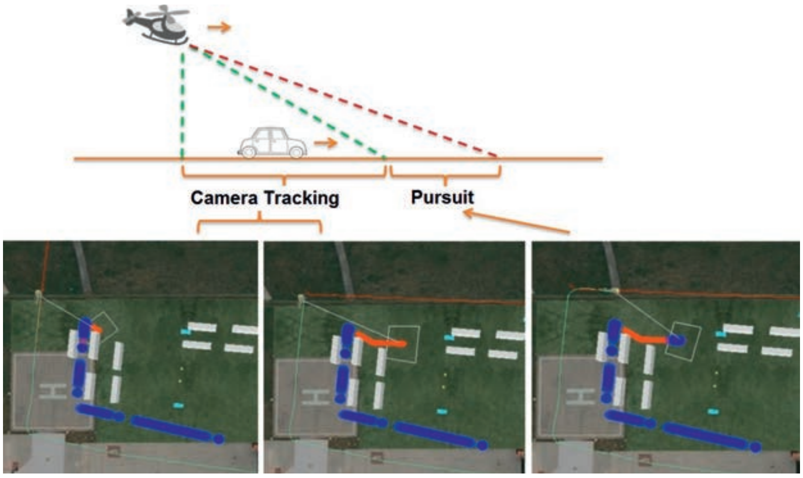
usually stay airborne for less than one hour. In contrast a UGS can operate for many hours if not days, thus allowing near-permanent surveillance. However, the data is taken from a frog's perspective resulting in much occlusion. Moreover, the wireless connection could be disrupted due to the presence of obstructing buildings and other ground structures. In the project, a fuel-powered helicopter from EADS was chosen as the UAS. Its maintenance is relatively easy, the components are inexpensive and the copter can carry sufficient payload for the purpose at hand. Figure 1 schematically shows the hardware components. The system features a commercial off-the-shelf autopilot that is guided by a pre-specified set of waypoints, which can be easily updated or adapted to flight conditions and the surveillance crew's demands. The on-board pan-tilt camera is controllable from a ground station, for example to search for obstacles on the ground that may obstruct the locomotion of the UGS. If obstacles are present, the path of the UGS may be adjusted. Telecommand and position information are transmitted through separate data links. The on-board computer handles route planning, marker detection and communication.

To meet requirements on payload and size, a four-wheeled vehicle was chosen as the UGS: the Mobile Experimental Robot for Locomotion and Intelligent Navigation (MERLIN) [5]. Figure 2 shows the hardware components of the UGS. A laser range finder is used for obstacle detection and the built-in pan-tilt-zoom camera delivers the video stream. Figure 3 shows the UAS and UGS tandem in operation.

KEY REQUIREMENT

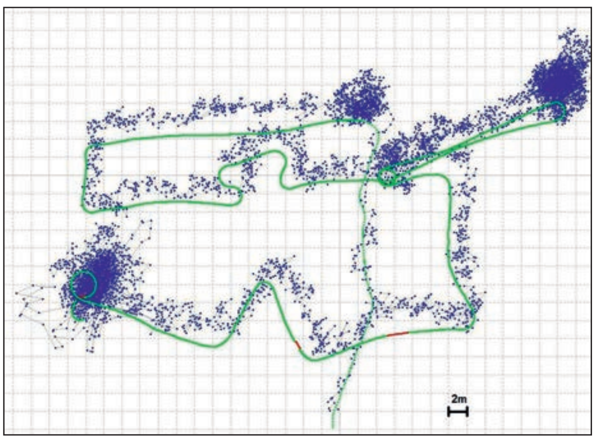
Precise and reliable positioning of the UAS and UGS requires special attention. GNSS with the currently available GPS and GLONASS is commonly used for outdoor positioning. GNSS suffers from errors introduced by ionospheric and atmospheric distortions of signals, satellite failures or multipath effects. As the UAS and UGS ▶

◀ *Figure 3, UGS and UAS in tandem at surveillance; the UAS follows the UGS autonomously.*



▸ *Figure 4, Simulation showing UAS path (orange line), obstacle detection and following the UGS path (red); camera footprint is indicated as a square on the surface. Right: pursuit of the vehicle when it is going to leave the tracking area to keep the target in sight. Blue: UGS track. White: simulated containers.*

▾ *Figure 5, Comparison of standard GPS track (blue) with the low-cost RTK GPS solution (green) shown on a 2m grid.*



move autonomously, real-time detection of anomalous or faulty GNSS signals is critical. Software was developed to detect and quantify noise, multipath or faulty signals, and these signals can be excluded from the positioning solution thus yielding higher integrity and quality. The real-time kinematic (RTK) solution enables a quality check on the positioning data. Many errors can be eliminated with two or more low-cost GPS receivers mounted on the UAS and UGS and using a base station allowing differential GNSS. When positioning is unreliable or not available, the potentially wrong GPS data is discarded and the systems automatically switch to fall-back solutions based on one odometer mounted on the central motor axis of the UGS and a yaw-axis gyrometer. Fusion of the speed data derived from the odometer and the attitude data of the gyrometer provides position and attitude of the UGS. On the other hand, odometer and gyrometer may also provide erroneous data introduced by wheel slipping and drift, respectively. Using GNSS positioning allows these errors to be detected and corrected when they occur. Hence, by using multiple data sources combined in a sensor data fusion algorithm, positioning remains accurate even when one of the sensors produces faulty data. When the UGS does not receive sufficient GNSS signals because of driving under foliage or meeting other signal blocking circumstances, for example, the odometer data keeps the UGS on track for several metres with a deviation of just a few centimetres.

OBSTACLE AVOIDANCE

Autonomous surveillance entails a pre-specified path, a position controller and most importantly obstacle avoidance. The latter requires the presence of 'eyes' that can capture the local environment ahead of the UGS. We compared three systems: the CamCube 3.0 [2], the Microsoft Kinect [3] and a laser scanner from Hokuyo [4]. The CamCube and Microsoft Kinect generate stereo images which potentially produce high detail; the laser scanner measures the range in slices. Theoretically the stereo images would allow the detection of subsurface obstacles. However, the images suffer from limited range and field of view and from overexposure when the sun shines directly into the camera. The Kinect is actually an indoor sensor for short ranges. Under outdoor conditions the laser scanner is superior to the 3D cameras. Therefore, the laser scanner was used as an eye for obstacle avoidance and an algorithm was developed to detect obstacles from laser scan data. Figure 4 shows a simulation in which the stationary UAS in the top-left corner (dark yellow) tracks the UGS (red dots) with the on-board camera.

USER INTERFACE

The prototype for this project, consisting of a UAS and a UGS operating in tandem, aims at assisting surveillance staff to monitor a container terminal. Since guards are not trained in operating robotic systems, the system should be as easy to control and user-friendly as possible. A browser-based human-machine interface developed in combination with the expert knowledge of a professional surveillance provider from Wilkon demonstrated the suitability of the graphical user interface (GUI) for use by laymen. Interviews with users revealed that security and easy use should be prioritised. The user interface was iteratively redesigned based on the surveillance staff's experiences. The users can adapt the on-screen layout to their personal and operational needs by changing the sizes and opening/closing tabs. A set of predefined layouts was also prepared based on the needs of flight operators, monitors of the data stream, supervisors and other possible user groups.

TEST

Figure 5 shows the path followed by the UGS during the final test. The blue dots show the positions as measured by the stand-alone, single-frequency GNSS approach. The green line shows the RTK positions. Obviously, the positions generated by the latter have a much higher precision. The trace of the UGS is easily visible. Red tracks indicate that the calculated position did not meet accuracy requirements. The final test followed a typical surveillance scenario. Although the routes between control points are pre-defined, the surveillance crew can catch up on the pre-specified route of the UGS at any time to divert to locations that require closer inspection. The UAS operates in conjunction with the UGS autonomously to provide an additional bird's-eye view or can be used separately. The ground station manages all interactions between the UGS and UAS, and both can be tracked by the surveillance staff in the control centre or by a guard doing his rounds carrying a small handheld device such as a tablet. What the UGS and UAS see in the form of video streams is also transmitted to the surveillance staff.

CONCLUDING REMARKS

This system can be adjusted for use in other fields of tele-operation. Depending on the application, sensors for measuring gas, temperature, radiation or other phenomena can be mounted on the platforms, which can also be equipped with solar cells. The approach allows to a reduction in the resources and training costs involved in controlling and co-ordinating autonomous robot systems.

ACKNOWLEDGEMENTS

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FURTHER READING

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