SkyTec Ireland

Unmanned Aircraft Systems Technology

ARCOPOL PLUS

Low-Cost Unmanned Aircraft in the Offshore Environment: Effectiveness and Constraints

ATLANTIC AREA
Transnational Programme

European Union

European Regional Development Fund

Introduction

In June 2013 the Halpin Centre for Research and Innovation at the National Maritime College of Ireland commissioned SkyTec Ireland (see Appendix 2) to carry out research on its behalf as part of the NMCI's commitment to Activity 3 of the ARCOPOL+ project.

Activity 3 is concerned with the upgrading and transference of tools for hazardous chemicals and hazardous noxious substance detection, forecasting and risk analysis. Through a number of actions, including an investigation of the role of unmanned aircraft for HNS spill location observations, the activity aims to improve end user expertise in regard to spill forecasting and spill tracking. The use of unmanned aircraft for spill observation is explored through actions 3.4.1 - a review of aircraft capabilities; action 3.4.2 - integration of zenithal pictures into Geographic Information Systems (GIS); and action 3.4.3 – use of rapidly adapted sensors for HNS spill monitoring. The NMCI is a contributing partner to this activity, which is managed by INTECMAR and IST.

SkyTec Ireland applied its knowledge of Small Unmanned Aircraft Systems (SUAS), acquired through several years 'hands-on' experience operating SUAS in the field, and familiarity with the Maritime environment gained by extensive manned helicopter piloting experience in the offshore Oil and Gas industry, towards:

- A review of suitable Small Unmanned Aircraft Systems for shipboard operations, emphasising the extent to which commercial off-the-shelf (COTS) airframes can be used to collect zenithal pictures suitable for integration of into GIS and to carry HNS spill monitoring sensors.
- Choice of a suitable platform, costing less than the guideline maximum of €30000, with which to undertake flight tests.
- Specification of a ship-borne test flight program.
- Execution of flights to explore the practicalities of ship-borne SUAS activities.
- Delivery of a workshop in which to examine the results of flight trials.

This report is organised into sections as follows:

1. Discussion of research questions and methodology choices.
2. Review of low-cost Maritime SUAS.
3. Goals of the flight campaign
4. Descriptions of missions and individual flights.
5. Lessons learned regarding the suitability of COTS SUAS for operations in the Maritime environment and the effectiveness of SUAS in the HNS spillage support role.
6. Conclusions.
7. Acknowledgements.
8. Appendix 1 – Bibliography.
9. Appendix 2 – SkyTec Ireland company profile.

1 Formulation of Research Questions and Choices of Methodologies

Our attempt to formulate research questions to probe the loosely defined goals listed previously began with a general survey of marine-capable SUAS. This preliminary investigation revealed a bewildering variety of SUAS purchasable for less than the suggested €30000 threshold, but none, judging from manufacturers claims, stood out as candidates for maritime operations. We concluded:

- No single aircraft could perform the diverse range of tasks we envisaged a HNS support aircraft being capable of;
- Purpose-built marine capable SUAS are primarily targeted at Military users with purchase costs significantly greater than the target budget;
- Automatic flight control system capabilities (autopilots) and ground-based equipment functionalities were similar across the range of airframes we examined.

Unable to identify a suitable make and model of aircraft with which to evaluate HNS spillage response tasks, we were unable to proceed with the practical aspects of this research.

However, low-cost unmanned aircraft, be they fixed-wing, helicopter or multi-rotor designs, employ flight controls systems that share inertial navigation sensor components and sensor data fusion strategies, flight control algorithms, and Global Navigation Satellite System capabilities. In fact, SUAS manufacture has evolved into a cottage industry whose innovative effort goes principally into airframe design; designs employ commercial-off-the-shelf or open source autopilots of which there are relatively few examples.

The aforementioned observation brought to mind an alternative strategy: independent assessment of the Maritime capabilities of airframes, autopilots and camera payloads in the Maritime context. Thus failure to identify a low-cost 'marinsed' airframe/autopilot/sensor package need not prevent us from making useful observations. And since our investigation of payloads is confined to the integration of data into Geographic Information Systems, and this is determined by compatibility of cameras with pre-and post-processing software applications, effectively our practical research need only be concerned with autopilot systems. Environmental factors that affect one autopilot will affect all others, and by extension, any class of airframe.

We therefore applied the following research strategy:

1) Review literature to the extent necessary to support our claim that at present no suitable low cost Maritime SUAS exists;
2) Execute an exploratory flight program with an airframe we could depend, even if for reasons of endurance and weather resilience that airframe might not be considered a maritime contender.
3) Investigate non-technical questions regarding Maritime use of SUAS. We wished to analyse our results in a broad range of contexts, including human-machine interaction, the manner in which pre and post-processing requirements might impact HNS spillage management

workflow, whether simultaneous UAS operations and ship are compatible, whether special skills are necessary for marine SUAS crew members, and the impact of legal constraints imposed by Aviation Authorities over use of unmanned aircraft might have on HNS spill response operations. We consider such matters to be equally as important as technological issues if we are to predict the manner in which and the extent to which SUAS tools may permeate niche applications such as HNS spill management.

Methodologies

Given the global nature of the unmanned aircraft industry, for which the Internet serves as the shop window for vendors and as the point of contact between manufacturers and aircraft users, we elected to limit our search to Internet Websites. We chose not to concern ourselves with aircraft systems borne of academic research; these are not available to HNS spill response decision makers at present, nor likely to be in the future. Searches of journals and academic publications seemed therefore inappropriate.

Test flying was planned with subjective analysis of results in mind; we predicted any contribution to the Arcopol Plus project would stem from our expertise and knowledge of SUAS operations and data handling. Our flight program was devised to raise awareness and pose questions, not to provide objective data

2 Review of Maritime SUAS

The purpose of this section is merely to illustrate strategies currently in use to adapt unmanned aircraft systems for Maritime use. Readers are invited to judge for themselves from the following images whether such systems are practical in the context of low-cost, rapidly deployed, HNS spill management support. We voice our opinions in section 5 (Discussion of Results).

Fixed-Wing Aircraft

We found only two approaches to fixed-wing aircraft marinisation: large aircraft are provided with deck mounted launch/arrest paraphernalia, aircraft small enough to be hand launched are sealed so they can be landed on water.

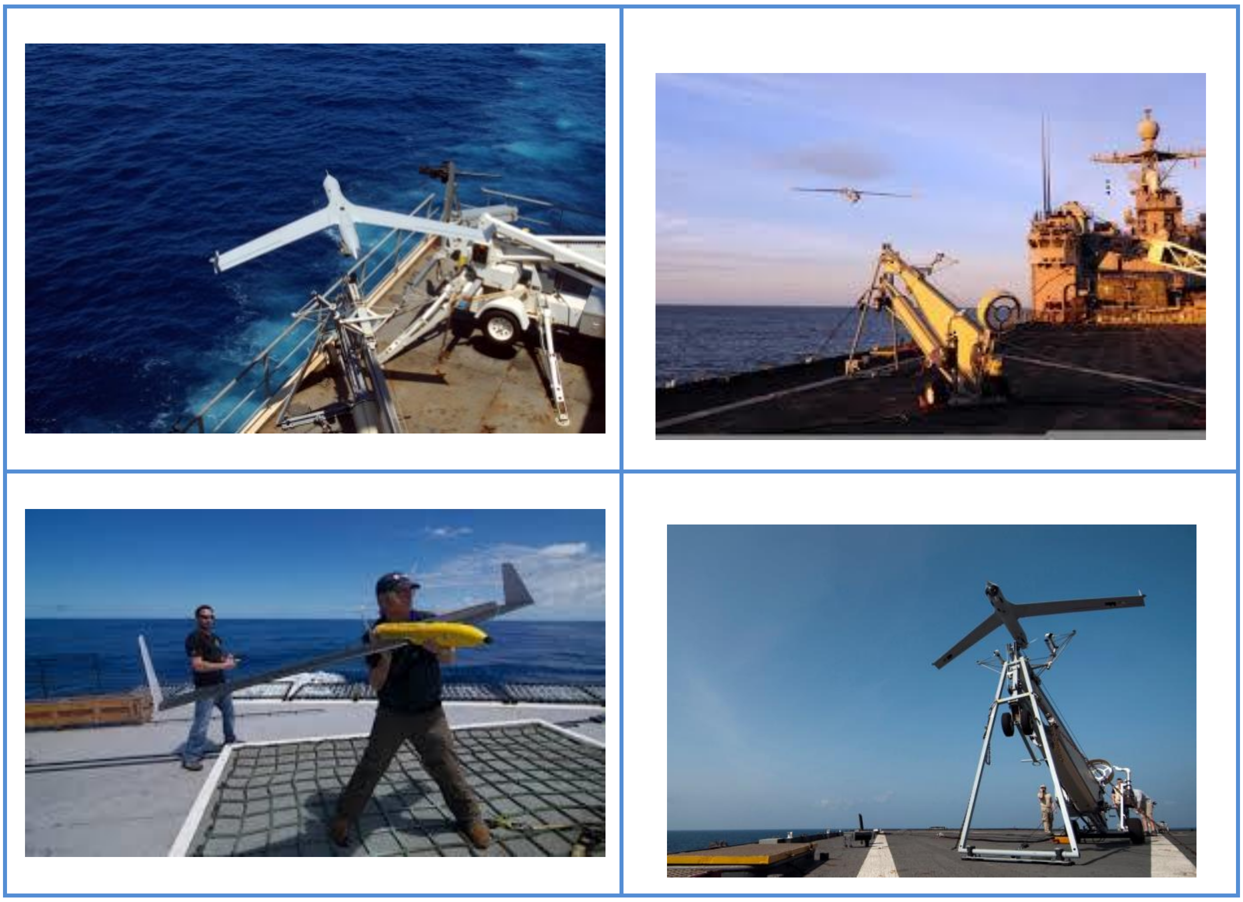


Figure 2.1 Deck launch systems

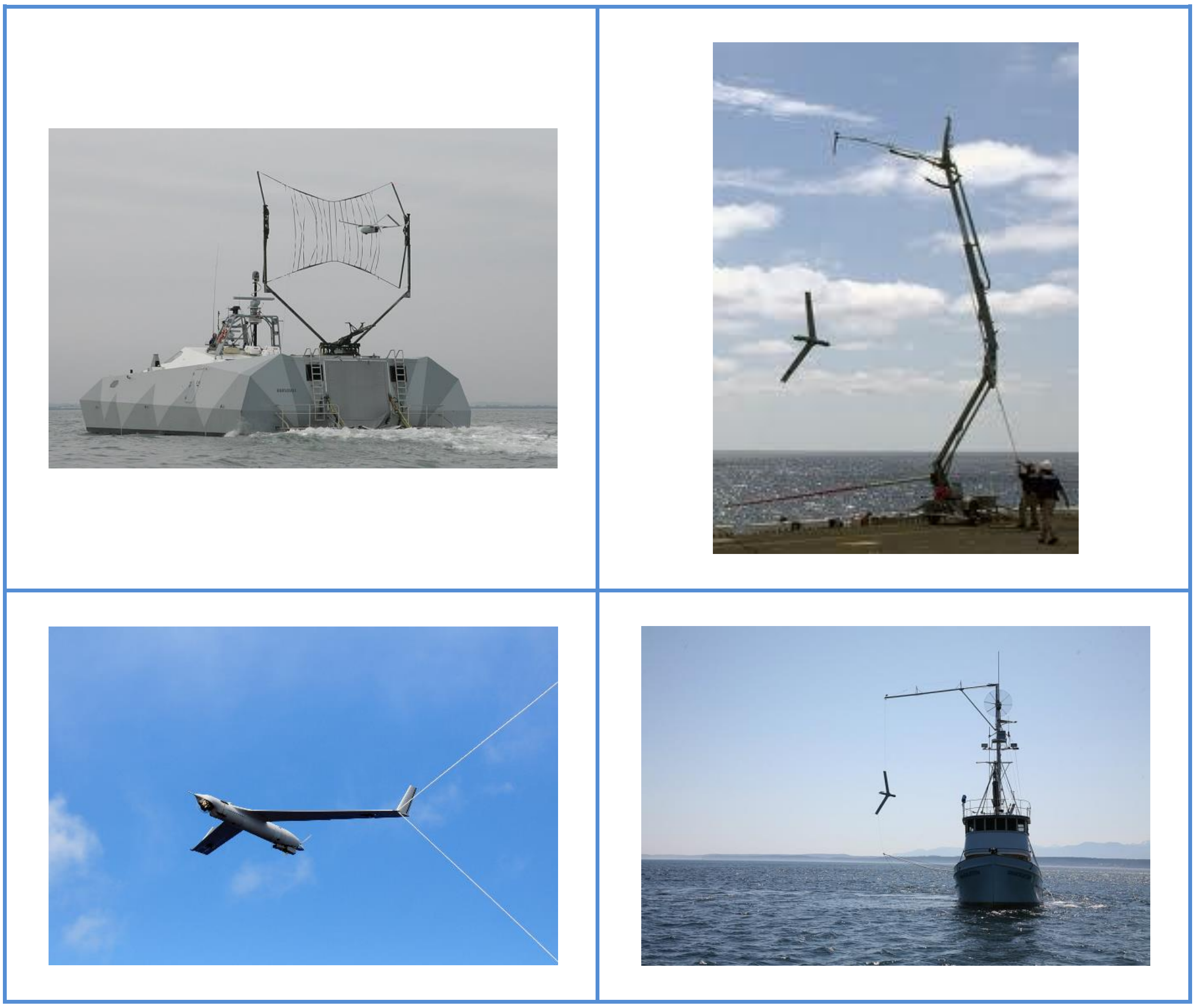


Figure 2.2 Arrester Systems

Figure 2.3 Amphibious Recovery Techniques

Helicopters

The only Maritime-specific adaptation we encountered is this harpoon system to locks the aircraft to the deck.

Figure 2.4 Deck Harpoon

Multi-Rotor Aircraft
We found only one instance of a waterproof multi-rotor UAS that might be considered marinised, (Figure 2.5, top right) although this example is too small to be of use offshore.

Although complete waterproofing is impractical for larger machines (weight penalty), protecting airframe with simple flotation device offers at least the possibility of salvage (see Figure 2.5, top left). Any of the airframes in Figure 2.5 could be similarly adapted.

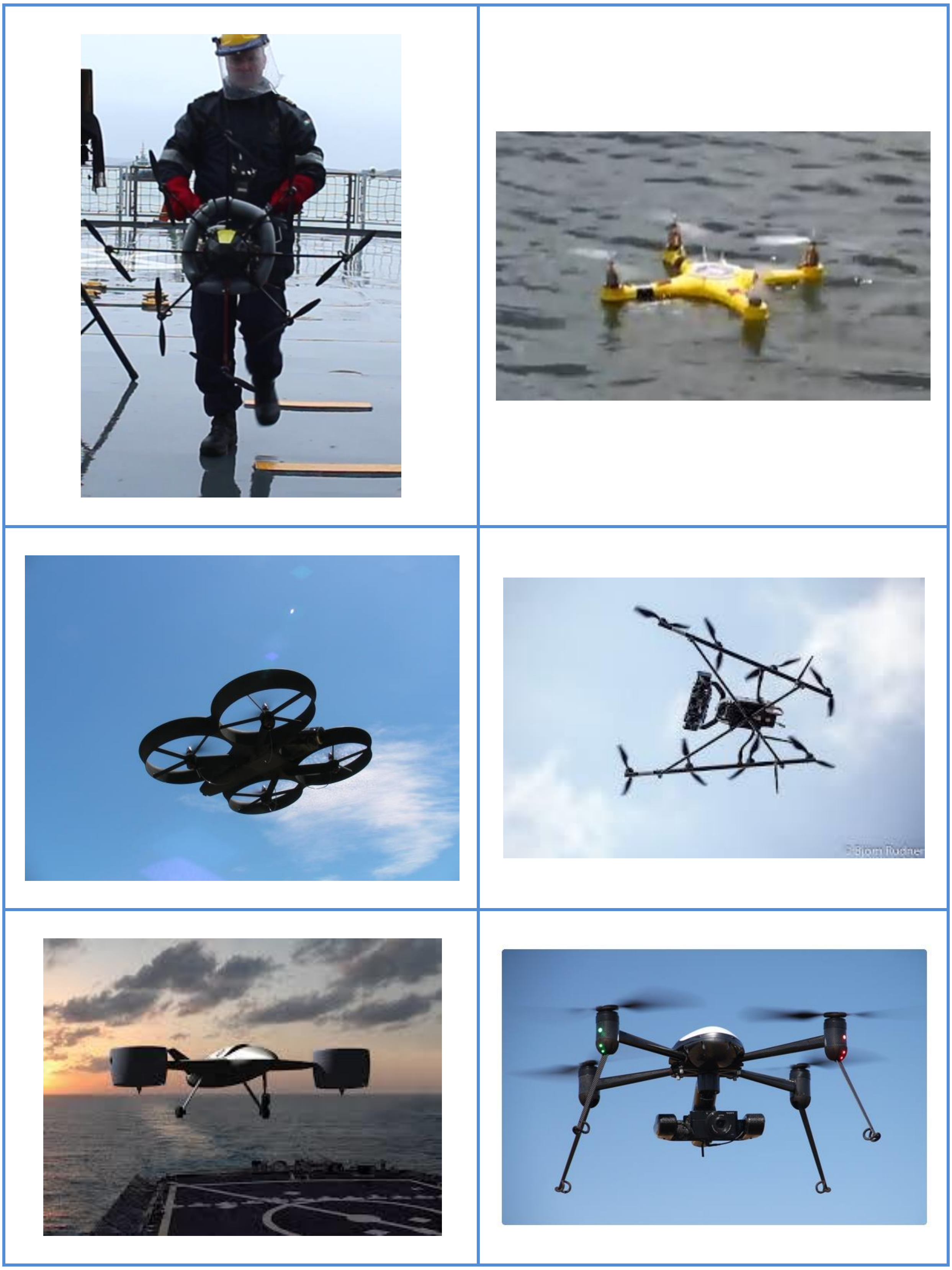


Figure 2.5 Multi-Rotor Airframes

Other Airframes

Lighter-than-air and flexible wing unmanned aircraft are unlikely to be robust enough for offshore use, but should not be ignored.

Figure 2.6 (Left to Right) Flex-Wing, Balloon and Dirigible UASs

Autopilots

The following sample of autopilots emphasises the fact that airframes and autopilots are evolving independently, and that a surprisingly large (and rapidly growing) community of Open Source autopilot developers exists.

Manufacturer	*Product*	*Description*
Procerus	Kestrel	Commercial ; all aircraft
MicroPIlot	2128	Commercial , top-of-the-range model boasts triple redundancy; all aircraft
MikroKopter	FltCtrl/NaviCtrl	Commercial ; multi-rotor aircraft
3D Robotics	ArduPilot	Open Source; all aircraft, also robotic land and water craft
DJI	WKM, NAZA, ACE	Commercial ; principally rotor-craft.
Papperazi Project	Various	Open Source, all aircraft
weControl	wePilot	Commercial ; rotorcraft
Gluonpilot	gluonpilot	Open Source; all aircraft
OpenPIlot	CopterControl	Open Source; multi-rotors
Tau labs	Various	Open Source; all aircraft

Table 2.1 Autopilots

3 Flight Campaign Decisions

General Strategies

In planning our flight program we drew on (often bitter) SUAS piloting experiences that led us to expect unwelcome lessons from even trivial steps into the unknown. We therefore contrived a sequence of trials with objectives that built on one another's outcomes. We also knew from experience that even simple experiments may produce information that later proves to be valuable; flights to explore simple, perhaps trivial, objectives could bring to light worthwhile data.

We were keen to demonstrate the diversity of data gathering tasks for which small unmanned aircraft might be considered, so aimed for breadth, rather than depth in our test flight objectives. For example the finale to our program deployed two unmanned aircraft systems in three data gathering roles on the same day, consecutive missions that demonstrate the utility and versatility of SUAS.

We analysed our results and drew conclusions from our observations whilst embracing the clear but unstated aim of the project: to offer those charged with implementation of HNS response policies realistic expectations regarding the suitability of current generation SUAS for spill management support.

Choice of Aircraft

As noted, our goal was to explore the influences of ship-borne environmental factors on MEMS sensor autopilots, therefore we took the decision to choose test bed airframes solely on practical criteria: portability, safety to operators during launch and recovery, suitability of the ground station in regard to pre-and post-processing activities, and availability of ancillary equipment.

The notion of operating helicopters on cluttered, possibly confined decks was fraught with insurmountable safety issues, given the projects short duration and limited budget. Similarly, the idea of using fixed-wing aircraft was found to be impractical. If the autopilot problems we anticipated had transpired, they most likely would have become apparent during launch or landing; the very times the aircraft would be most vulnerable and the problems most difficult to contain. Moreover, use of a fixed-wing aircraft would preclude experiments for which hover ability would be prerequisite.

Thus for ship-borne tasks we chose a multi-rotor airframe small enough to be launched and recovered by hand, but large enough to lift a good quality (4000 x 3000 pixel sensor) digital camera. This airframe can undertake oblique and orthogonal photographic tasks, limited only by 14 minute endurance. A larger, more powerful, but less versatile (10 minute endurance) aircraft was pressed

into service for sensor payload experiments. Both aircraft are eight-rotor designs with identical MikroKopter flight control systems.

The smaller of the two aircraft, a MikroKopter OktoKopter XL, is equipped with a motion-stabilised camera mount, camera remote control system (which includes remote exposure setting control), and a video downlink. Other than the addition of a foam 'life jacket', the aircraft is entirely standard. We used this aircraft with a 'Follow-Me' system, a stand-alone GPS receiver, interface board and radio transceiver that acts as a beacon over which the aircraft maintains station. The system continuously updates the aircraft with its latitude and longitude which the autopilot registers as a target waypoint.

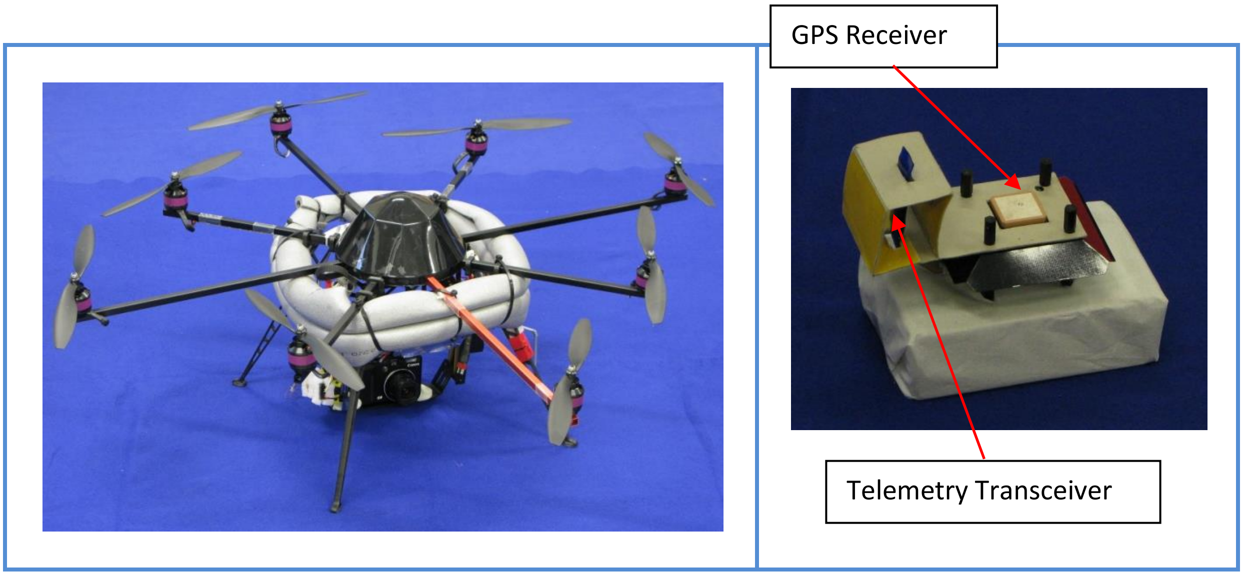


Figure 3.1 MikroKopter OktoKoper XL (Left) MikroKopter 'Follow-Me' Beacon (Right)

The larger aircraft, a Quadrocopter 'CineStar8' (Figure 3.2), is a heavier version of the OktoKopter featuring more powerful motors and larger propellers. We replaced the camera gimbal with a foam equipment box in which, and to the outside of which, we mounted a Sea-Fi Wireless Harbour Network radio, a computer network hub, a camera-top encoder, a serial data encoder, and a Go-Pro camera. We suspended a water temperature sensor system on an 8m cable beneath the equipment box. The temperature sensor consists of a float containing processing electronics from which a thermometer probe extends a few inches underwater.

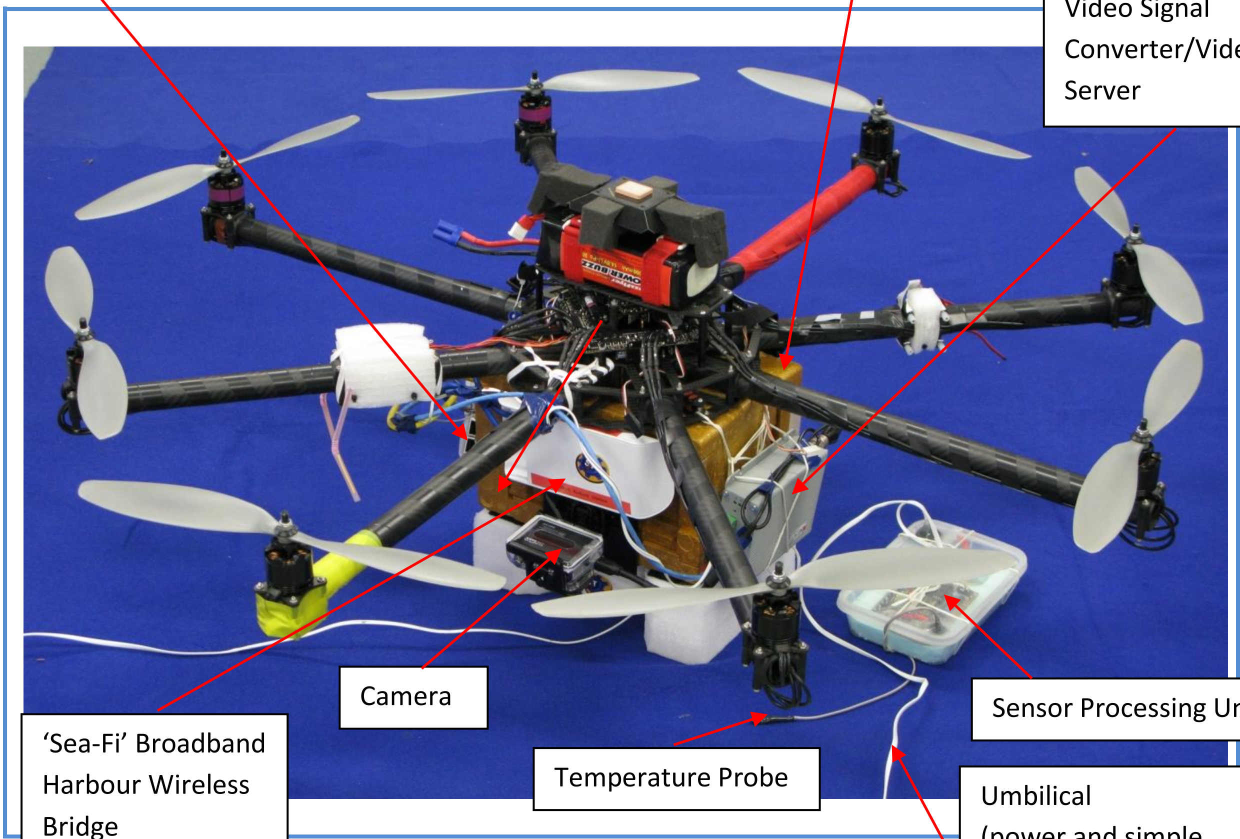


Figure 3.2 – CineStar 8 with remote sense package.

Flight Program Goals

1) To Survey Irish Naval Service (INS) vessel decks to find favourable areas for launching and recovering SUAS.
2) To become familiar with flight characteristics of typical SUAS autopilot Miniature Electro-Mechanical Sensors and Magnetometers in proximity to sources of magnetic interference and electro-magnetic radiation.
3) To evaluate semi-autonomous flight features commonly employed by pilots to assist with manual control of SUAS, for example during roving exploratory flights to identify and photograph debris, from a moving ship.
4) To test of autonomous flight functions that might be used during zenithal image acquisition, dipping (water testing or sample collection), or air quality testing.
5) To evaluate feasibility of tethered flight, for example when deploying a SUAS to relay wireless communications or extend the radar horizon.

The Flight Program

The flight program, which consisted of 16 flights and 2 hours 25mins of flight time, took place between 8th September 2013 and 6th February 2014. The following missions were undertaken:

1. Flights from docked ship.
2. Flights from a ship at anchor.
3. Flights from a ship underway.
4. Multi-Role HNS spillage investigation exercise.

4.1 Flights from a Docked Naval Vessel (LÉ Eithne), 8th September 2013

Aims

This preliminary step in the flight test program set out to establish whether Miniature Electro-Magnetic Sensor (MEMS) autopilot systems would function normally on board a steel hulled and ship and what effects the ship's radio and radar equipment might have on it. In particular we wished to determine how the Magnetometer sensor fared in proximity to shipboard ferrous structures and the extent to which Magnetometer errors, should they occur, interfered with overall autopilot function.

We also used this trial to inspect the decks of other INS vessels in the harbour at the time, in order to plan launch/recovery strategies for later trials.

Flight Program

Before flight, we planned to investigate distortion of Earth's magnetic field in the deck area using a hand-held magnetic compass and SUAS telemetry.

We then planned to conduct a short test flight to confirm normal autopilot function before making longer flights to reconnoitre ships in the dockyard basin. We wished to plan how we might deploy equipment on various decks, and to practice flying in close proximity to the Eithne's superstructure and antennae.

Results

Surprisingly, we found the aircraft's magnetometer to be unaffected by its proximity to the steel deck. It gave normal compass readings except when in very close proximity to massive objects, for example a capstan.

Light wind conditions posed no controllability issues for the pilot, who flew standard photography sortie, i.e. manually controlled loitering to shoot photos. The aircraft was flown in the standard configuration for this mission profile: stabilisation of height, position and heading hold.

The Eithne's open helicopter deck proved ideal for our SUAS operation; however our survey of other INS vessels showed this expanse of open deck to be exception rather than the rule (see Figure 4.4.2). Nevertheless, we were confident that using a hand launch/hand catch technique we would be able to operate from any of the ships we inspected.

Figure 4.1.1 Launch and recovery from the Eithne's open deck posed no problems.

Figure 4.1.2 Cluttered back decks, such as those of ships in the background, are common on INS vessels (Left), Flight in close proximity to the ship's structure proved uneventful (Right).

Figure 4.1.3 A panoramic view of the Navy Docks on Haulbowline Island with Cork harbour and Cobh Cathedral in the background, created from images captured during this mission.

4.2 Flights from an anchored ship (LÉ Emer), 10th September 2013

Figure 4.2.1. Preparations for Exercise Ibis 2.

SkyTec Ireland was invited to join LÉ Emer on the day Combined Defence Forces Exercise Ibis 2 at Castletownbere, Co.Cork. Figure 4.2.1 shows the Army's 'Orbiter' UAV being prepared for flight in the foreground, the LÉ Emer in the background (indictated by the arrow). Figure 4.2.2 shows the LÉ Emer in greater detail. Figure 4.2.1 was captured by the SUAS before the aircraft and ground station were deployed on the LÉ Emer.

Figure 4.2.2. LÉ Emer

Figure 4.2.3. This small craft alongside the LÉ Emer transported SkyTec equipment and crew to the ship; crew and equipment boarded by rope ladder.

The SUAS crew was tasked with exploration of a shipwreck. In this exercise the wreck was antique, but in the context of HNS spillage response, a recent shipwreck with the possibility of pollution leakage might be envisioned. The mission called for the aircraft to store on-board high quality images for later retrieval, also to stream live video to the Emer for evaluation by the HNS spillage response team in real-time.

Aims

To evaluate SUAS semi-autonomous performance at maximum range, a) to raise the crew's confidence in its ability to cope with ship-board operations, and b) to evaluate problems of over-water photography.

Flight Program

We planned to fly once to the wreck in order to establish transit time, then to return as many times as possible to gather data. In addition to capturing general high resolution views of the wreck, we hoped to explore the subject from as many angles as possible in order to determine whether perceived water colour changes according to the relative direction of the sun.

The aircraft was to be under manual control for the entire mission, in a mode where the aircraft can be commanded to hover in its present location, for example during photography.

The operation was identical to the general aerial photographic mission profile with which the SUAS crew were well versed, however the distance of the target from the ship called for special

considerations regarding battery endurance. With the real possibility that if the aircraft loitered too long over the target, the battery might become exhausted during the return flight, the first flight was strictly evaluative allowing only conservative exploration of the wreck .

Figure 4.2.4 Target wreck viewed from 250m (approximately half the distance between the wreck and the ship)

Figure 4.2.5 Uncropped image taken at the aircraft's closest approach to the wreck, approximately 50m distant.

Results

A hand launch/catch recovery technique proved well suited to the Emer's relatively cramped deck area. Whether or not these operations would have been so straightforward if the vessel were pitching, rolling and heaving, or if a larger SUAS had been used, remain matters of conjecture.

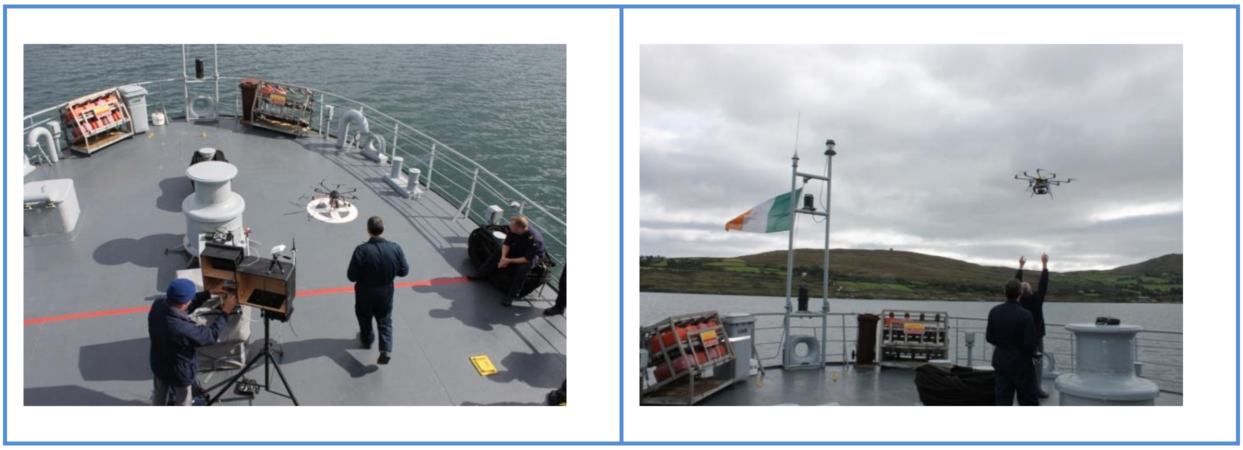


Figure 4.2.6 (Left) Preparing the ground station; (Right) Demonstration of the overhead hand launch/hand catch recovery technique.

The wreck proved to be over 500m from the ship, which posed a problem because Irish Aviation Authority regulations forbid flight beyond this distance. The crew flew as close as possible to the wreck and zoomed the camera in on the subject, but despite good image quality photos reveal little of interest.

Figure 4.2.7 Details of the wreck; resolution approximately 2cm.

Because the aircraft could not be flown right up to the wreck, we decided little more could be gained by further photography. To minimise the risk to our aircraft by prolonged over-water flying, we decided to curtail the flight program. We did take the opportunity, however, to photograph the Emer and her crew to record the ship's final patrol.

Figure 4.2.8 Views of the LÉ Emer and her crew

4.3 Flights from a ship underway (LÉ Eithne), 30th January 2014

Aims

- To explore ad-hoc mobilisation of a SUAS on a vessel-of-convenience in regard to the integration of SUAS assignments with ship operations.
- To evaluate the extent to which relative wind and deck motion complicates launch, recovery and manual control of a multi-rotor SUAS.
- To highlight shortcoming of 'return-to-home' radio control failsafe protocols.
- To investigate performance of a tethered multi-rotor SUAS.

Flight Program

We planned a series of manually controlled flights of increasing difficulty. The objective of the first flight was to assess the feasibility of launching the aircraft from and landing it in a catcher's hands with catcher, pilot and aircraft all in motion relative to the earth.

If take-off and landing proved to be achievable, we planned to progressively expand our repertoire of manoeuvres, beginning by offsetting the aircraft increasing distances from the ship to simulate recovery from a survey sortie, then generally flying in close vicinity to the ship both to assess the degree of skill required to fly the aircraft on various headings relative to the pilot, and to ascertain whether the ship's radar and radio equipment interfered with aircraft telemetry or video signals.

We were not concerned with autonomous flight, there being no reason to suspect aircraft would fly pre-programmed waypoints any differently over water than over land.

We also planned to test the performance of a 'Follow-me' beacon, principally to demonstrate that with it in use the aircraft would maintain station above the ship with the ship travelling at normal speed without the need for pilot commands; and to conduct tethered flights to determine whether the aircraft remained stable and therefore whether this class of SUAS could be used for surveillance or data gathering as a powered kite.

Results

Our first reportable finding relates to events that transpired during the planning of these flights; during processing of our request to the Irish Aviation Authority for permission to operate in the harbour (necessary because the harbour lies under controlled airspace). Our application was unexpectedly rejected, partly because Air Traffic Control (ATC) was not satisfied that dependable communications between themselves and the pilot could be assured.

Eventually we negotiated a solution, but in areas not so well served by phones communications, and for less experienced operators, permission from ATC for ship-borne operations in controlled airspace might be difficult to elusive.

On the day of the trials, compliance with ATC regulations caused further problems. First we experienced a delay due to the appearance of a Coast Guard helicopter which landed at the nearby Naval Base. Regulations forbid SUAS from being flown within 2km of another aircraft, therefore we elected to delay until the helicopter had left the area, in case its flight path conflicted with our mission. Soon after the helicopter departed, weather conditions at Cork airport deteriorated and ATC withdrew our clearance to fly. Despite clear weather over harbour, it was conditions at the airport that dictated ATC protocols and these did not permit visual flight in Cork airspace. We were also constrained by the presence of another SUAS operator elsewhere in the area: ATC would only permit one unmanned aircraft to be airborne at any time.

Eventually weather at Cork airport improved, despite moderate rain five flights over the harbour were completed.

Figure 4.3.1. Ground track of SUAS harbour flights

Launch and recovery proved uneventful; matching the drone's speed with the ship at ground speeds up to 6kts proved not to be difficult: not a surprising result given very slack wind conditions.

However, during all flights aircraft telemetry reported that the aircraft was further than 500m from 'Home' (the geographic location at which the aircraft's motors started) and raised an alarm. The warning is necessary because 500m is the maximum range between aircraft and pilot permitted by

IAA regulations, however the aircraft became more difficult as the autopilot attempted to fly the aircraft to the point at which the 500m boundary was breached.

During later flights we tried, unsuccessfully, to remain within 500m of the initial launch point by turning the ship. Once first raised the alarm persisted even though telemetry indicated it was within 500m of home.

This behaviour is a MikroKopter idiosyncrasy, so we did not dwell on its implications, however it the author considers it to be representative of typical consequences to be expected when attempts are made to use autopilots for unusual missions. Whether aircraft required to undertake specific tasks for which autopilot customisation may be required are best served by commercial or Open Source autopilots is one developers should bear in mind.

Despite having to mildly ‘fight’ the autopilot, the pilot was able to retain control of the aircraft and, during range alarm free periods, successfully manoeuvred the aircraft in close proximity to the ship as planned with no untoward effects from ship’s radar and marine radio (VHF) communication systems (the output power and transmission details of these systems is not known).

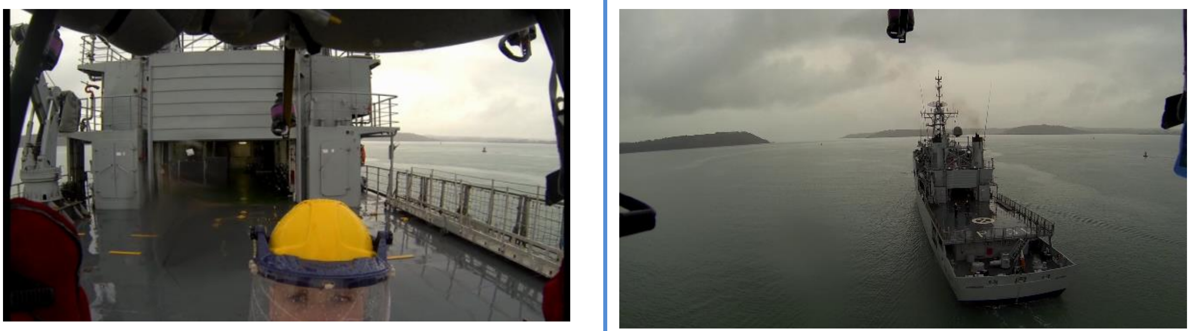


Figure 4.3.2 (Left) Preparing to launch; (Right) SUAS-eye view of the LÉ Eithne

The ‘Follow-Me’ system could not be used, we suspect it malfunctioned due to rain.

Tethered flights were an unexpected success, the aircraft remained docile even when disturbed by the tether cord. At first the pilot ‘helped’ the autopilot to keep station with the ship, but even when the autopilot was allowed free reign, the aircraft remained stable.

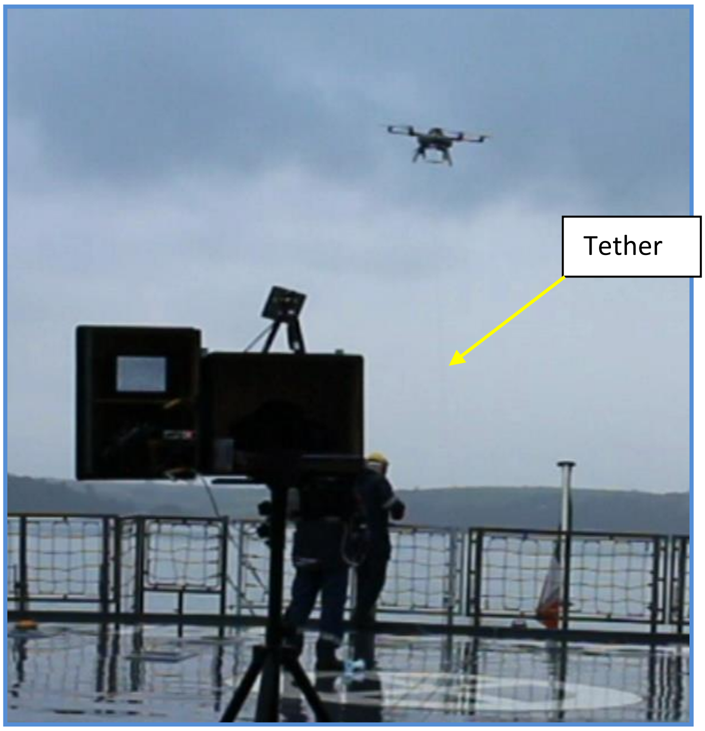


Figure 4.3.3 Tethered SUAS Trials

Figure 4.3.4 Capstan around which the tether became tangled.

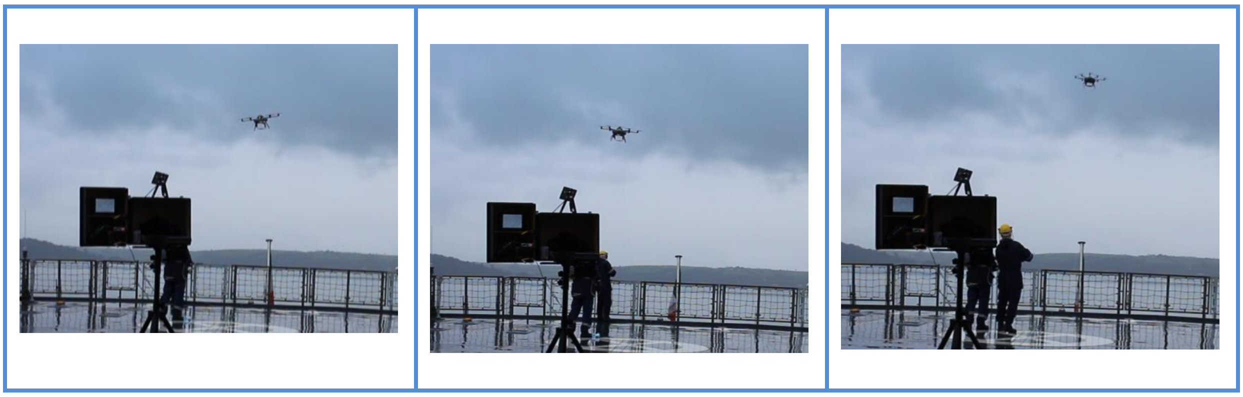


Figure 4.3.5 Example of attitude excursions observed during tethered flight.

As the tethered flight mission drew to a close and the aircraft descended towards the helideck, the cord became tangled around a capstan on the deck below (see Figure 4.3.3, top image). Despite these attitude excursions the aircraft remained aloft and was successfully recovered.

The aircraft was configured to fly in ‘Dynamic Position Hold’ mode throughout these tests. In this mode the autopilot attempts to hover the aircraft at a geographic datum that can be re-located by movement of the pilot’s control joystick. Tethering without GPS moderation (i.e. with the autopilot attempting only to keep the aircraft level) was deemed too risky to attempt until more was known about the aircraft’s behaviour when restrained. This test, and tethered flight with the ‘Follow Me’ system, would be candidate objectives for future trials.

4.4 HNS Coastal Spill Investigation Exercise, 6th February 2014

Aims

- To produce an illustrative data-set using typical aerial photogrammetry techniques in order to explore the difficulties of georeferencing and orthorectifying aquatic scenes.
- To assess the challenges of precision over-water oblique photography.
- To demonstrate an innovative approach to sensor integration and data dissemination.

Flight Campaign

In order to tackle our aims in a realistic manner, we contrived a plausible HNS spillage incident. Although for reasons of convenience we launched and recovered the aircraft from land, the results of previous trials demonstrate that the SUAS could have been deployed from a stationary vessel.

We envisioned a scenario in which seal and sea-bird carcasses have been found in discoloured sand in an inaccessible beach. A semi-submerged barrel has been spotted near the foreshore; labels on the barrel's lid lead the local authority to suspect the barrel contains chemicals. The presence of dead creatures suggests extremely hazardous water-borne contamination, therefore a HNS spillage investigation is launched.

Until risks are known and appropriate protective apparel can be issued, human intervention is undesirable. SUAS are tasked a) to sample water in the vicinity of the suspected pollution source with a chemical sensor in order to identify and map the extent of contaminants, sensor data is to be transmitted globally via the Internet to pollution control centres for real-time expert analysis, b) to conduct a visual survey of the barrel seeking clues of its contents from labels and gathering any other information pertinent to the clean-up effort, and c) to gather zenithal images of the foreshore and from them generate an orthorectified photomosaic and Digital Terrain Model, needed to plan deployment of vehicles and earth-moving equipment, and to estimate the quantity of contaminated sand.

To simulate rapid response, and to accurately reflect weather-sensitive nature of SUAS operations in Ireland which depend on windows of opportunity, the data-gathering effort was constrained by a requirement to conduct all flights in a few hours. Three missions were flown consecutively:

1. Orthophotography (3 flights)
2. Visual Inspection (2 flights)
3. Dipping survey (2 flights)

Orthophotographic Survey Preparation

In keeping with our goal to simulate a rapid response scenario, we set ourselves a realistic time limit of one hour in which to gather data (i.e. three flights). We estimated the strip of foreshore to be 200m x 50m; given the photogrammetric software's fundamental requirement for at least 75% overlap between images, we needed an image footprint of 80m by 60m which could be achieved by flying at 85m and using a moderately wide-angle lens (equivalent to 35mm focal length lens on a 35mm film camera). At this height each pixel in the camera's sensor would cover approximately 2.5cm x 2.0cm on the ground; making due allowance for JPG compression artefacts, motion blur and vibration etc. we expected resolution to be at least 4-5cm. The site could be surveyed by traversing four lines spaced lines 15m apart, taking photographs every 12m (a total of seventy waypoints).

We wished to minimise non-orthognality of our raw images, therefore adopted a 'stop-go' strategy at each waypoint, triggering the camera a few seconds after arrival at the waypoint. This tactic allows time for the aircraft to adopt a stable attitude and for the camera gimbal to settle before each shot.

Visual Inspection Preparation

The visual inspection flight was expected to be a data gathering exercise for the purpose of providing material for discussions of technical photography. We planned to photograph the barrel in as much detail as possible, choosing viewing angles and exposure settings to illustrate our points.

Dipping Survey Preparation

We employed a workflow honed during previous tests of the sensor aircraft. We found it impossible to judge the precise location of the aircraft relative to the dipping target without actually lowering the probe into the water. Finding the target by this method proved imprecise and time consuming. We therefore added a vertical camera to the sensor payload; this allowed the operator set the aircraft exactly above the target whilst recording its geographic coordinates via telemetry.

For the dipping survey two flights were planned: the first to ascertain the target's GPS coordinates and to establish the correct heights to program waypoints with; the second flight to conduct a nine dip survey in a grid pattern. During both flights data was streamed from the aircraft via a broadband wireless LAN to a PC.

Results

1) OrthoSurvey

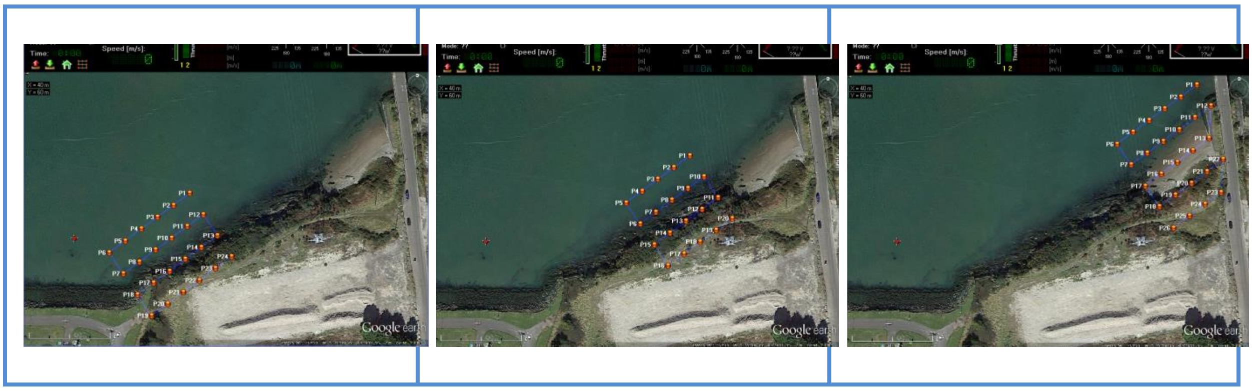


Figure 4.4.1 Each flight consisted of about 24 waypoints to cover a total area of 200m x 50m.

Nr.	Time	Radius	WP-Event	Climb rate	Altitude	Heading	Speed	CAM-Nick	Prefix	Latitude	Longitude
1	12	10	100	10	85	55	50	AUTO	P	51.8350122	-8.3023478
2	8	10	100	10	85	55	30	AUTO	P	51.8349503	-8.3024909
3	8	10	100	10	85	55	30	AUTO	P	51.8348884	-8.302634
4	8	10	100	10	85	55	30	AUTO	P	51.8348265	-8.3027771
5	8	10	100	10	85	55	30	AUTO	P	51.8347646	-8.3029202
6	8	10	100	10	85	55	30	AUTO	P	51.8346547	-8.3027943
7	8	10	100	10	85	55	30	AUTO	P	51.8347167	-8.3026511
8	8	10	100	10	85	55	30	AUTO	P	51.8347787	-8.3025079
9	8	10	100	10	85	55	30	AUTO	P	51.8348407	-8.3023647
10	8	10	100	10	85	55	30	AUTO	P	51.8349027	-8.3022215
11	8	10	100	10	85	55	30	AUTO	P	51.8347928	-8.3020955
12	8	10	100	10	85	55	30	AUTO	P	51.8347309	-8.3022386
13	8	10	100	10	85	55	30	AUTO	P	51.834669	-8.3023817
14	8	10	100	10	85	55	30	AUTO	P	51.8346071	-8.3025248
15	8	10	100	10	85	55	30	AUTO	P	51.8345452	-8.3026679
16	8	10	100	10	85	55	30	AUTO	P	51.8344353	-8.302542
17	8	10	100	10	85	55	30	AUTO	P	51.8344973	-8.3023988
18	8	10	100	10	85	55	30	AUTO	P	51.8345593	-8.3022556
19	8	10	100	10	85	55	30	AUTO	P	51.8346213	-8.3021124
20	8	10	100	10	85	55	30	AUTO	P	51.8346833	-8.3019692

Figure 4.4.2 Detailed view of a MikroKopter waypoint file.

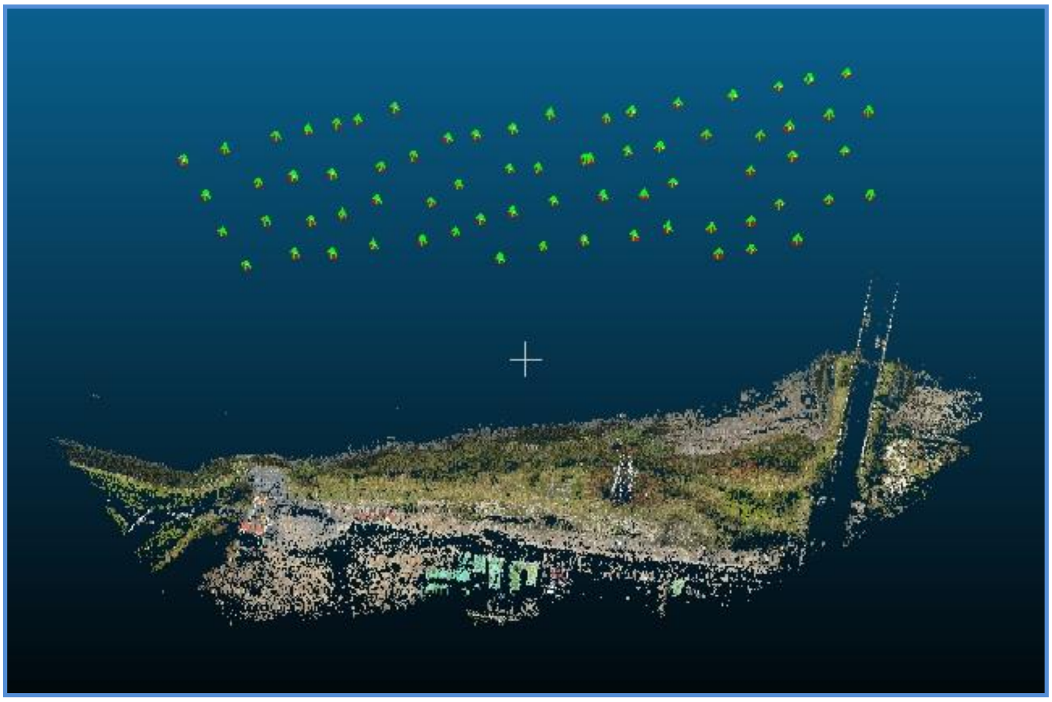


Figure 4.4.3 Sparse point cloud modelling the entire area. Each coloured point corresponds to a feature recognized by photogrammetry software in adjacent images. Each green pyramid represent a camera: the apex of the pyramid represents the lens focal centre, the red rectangles beneath it represents a projection of the camera's sensor towards the subject, displaced downwards by the lens focal length. All distances in the model are relative to the camera's internal dimensions.

Figure 4.4.4 Raw images after being scaled, rotated and georeferenced with GPS data extracted from the aircraft's navigation log file. Images are shown overlaid with the aircraft's ground track (also extracted from the autopilot navigation file) and viewed on Google Earth.

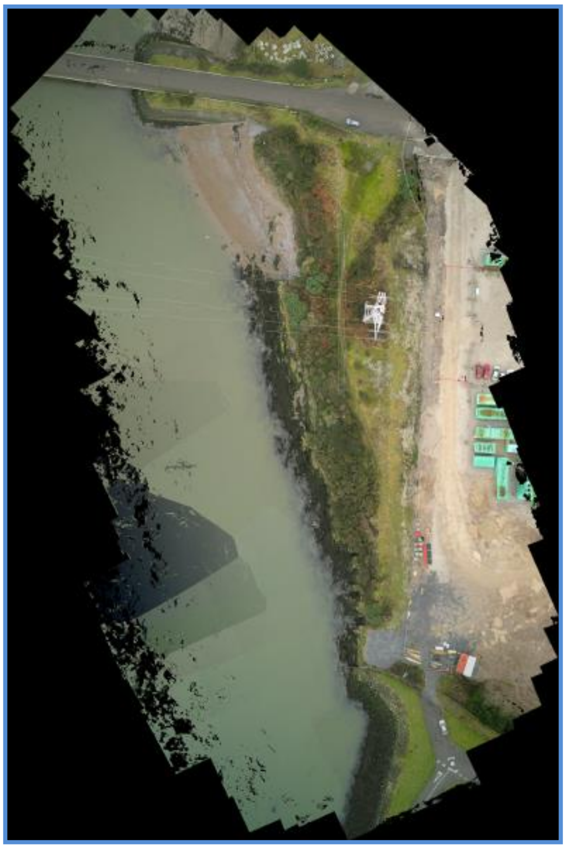


Figure 4.4.5 Orthorectified photomosaic of the foreshore. If the geographic coordinates of a number of ground points are known, either as result of a terrestrial survey carried out in tandem with aerial photography, or by inspection of existing georeferenced imagery or a map, this image could be directly integrated into any GIS that features tools to project raster images to a local coordinate system (e.g. GRASS, TatukGIS, Mapinfo Professional).

Figure 4.4.6 Scenes extracted from the orthomosaic showing the level of detail achieved

2) Oblique Photography Results

Figure 4.4.7 The ground station (left); Hovering near the barrel (right).

Figure 4.4.8 Detailed views of the barrel.

3) Dip Test Results

Figure 4.4.9 Ground track of the exploratory flight to survey the barrel's geographic coordinates.

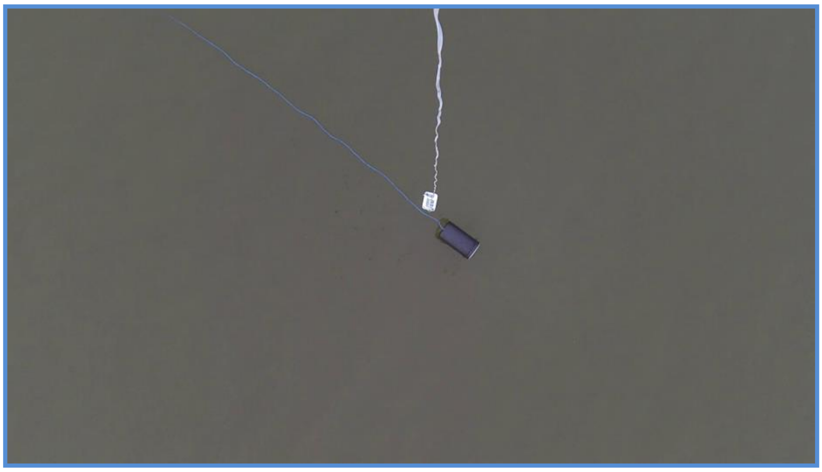
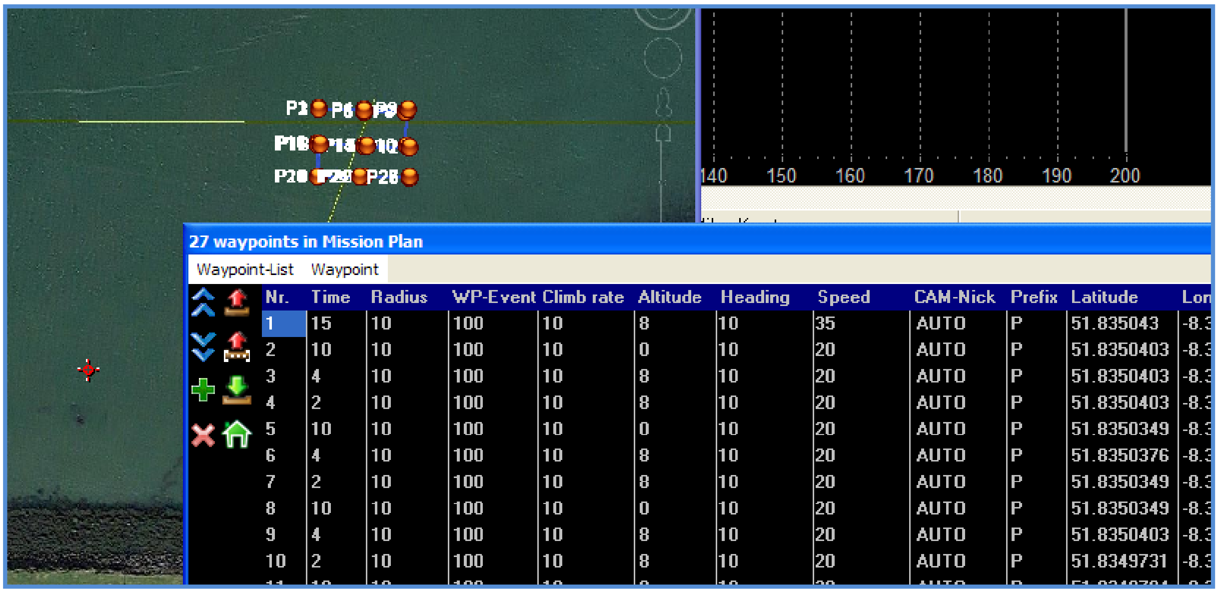


Figure 4.4.10 Snapshot extracted from the video captured by the aircraft mounted camera – at this instant the aircraft's location was recorded in the ground station as a temporary waypoint. A pre-programmed survey grid was re-plotted onto this central waypoint.

Figure 4.4.11 Survey grid waypoints distributed in a three-by-three grid spaced approximately 5m apart.



Nr.	Time	Radius	WP-Event	Climb rate	Altitude	Heading	Speed	CAM-Nick	Prefix	Latitude	Lon
1	15	10	100	10	8	10	35	AUTO	P	51.835043	-8.3
2	10	10	100	10	0	10	20	AUTO	P	51.8350403	-8.3
3	4	10	100	10	8	10	20	AUTO	P	51.8350403	-8.3
4	2	10	100	10	8	10	20	AUTO	P	51.8350403	-8.3
5	10	10	100	10	0	10	20	AUTO	P	51.8350349	-8.3
6	4	10	100	10	8	10	20	AUTO	P	51.8350376	-8.3
7	2	10	100	10	8	10	20	AUTO	P	51.8350349	-8.3
8	10	10	100	10	0	10	20	AUTO	P	51.8350349	-8.3
9	4	10	100	10	8	10	20	AUTO	P	51.8350403	-8.3
10	2	10	100	10	8	10	20	AUTO	P	51.8349731	-8.3

Figure 4.4.12 Note three waypoints per dip location and manner in which altitude and time between waypoint settings programs the 'dip' action.

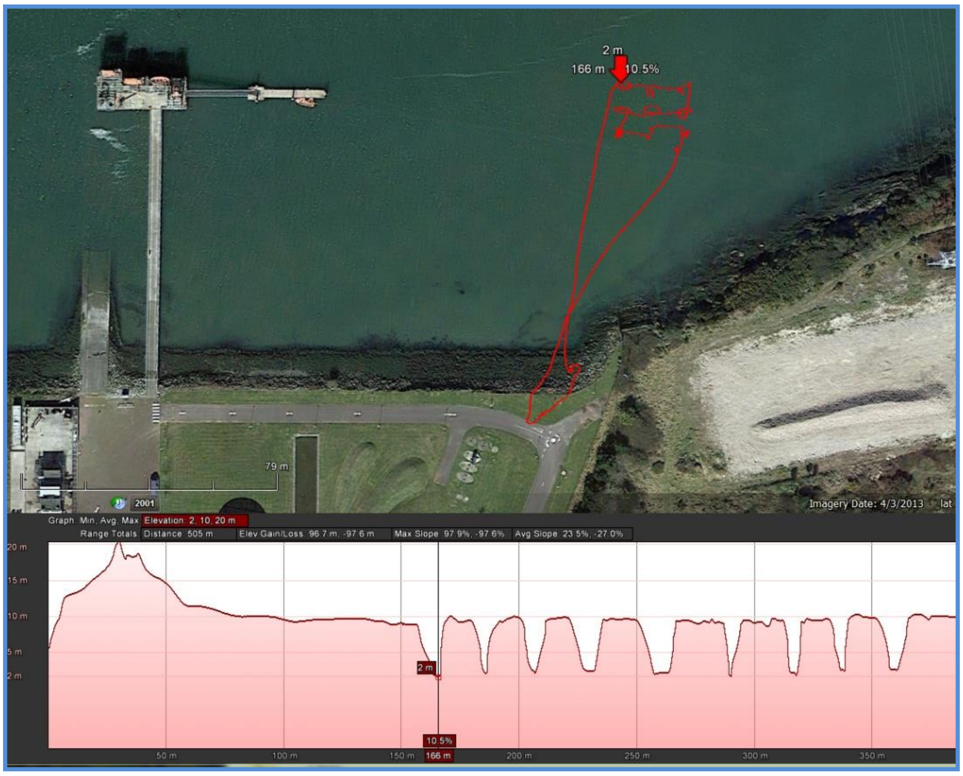


Figure 4.4.13 Data extracted from the aircraft's navigation log showing ground track and below the map a graph of aircraft height plotted against time (across the page, from left to right).

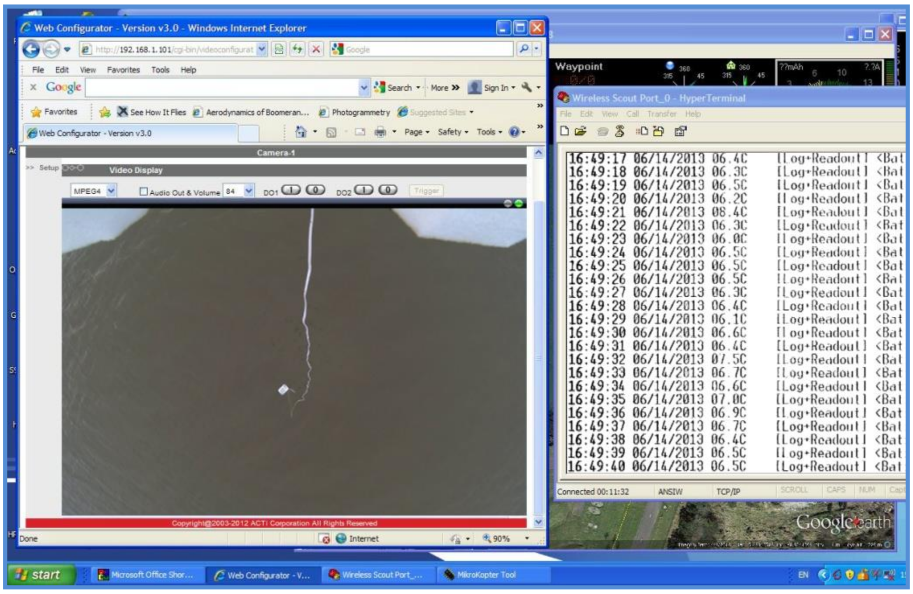


Figure 4.4.14 Screenshot of ground station showing simultaneous display of temperature data and live video stream.

Figure 4.4.15 Launch of a mission…

Figure 4.4.16 Dipping in progress

5 Discussion of Results

In this section we examine the results of our trials in the following contexts:

- The compatibility of low-cost unmanned aircraft airframes and autopilots with offshore weather and mobile, dynamic launch and recovery sites.
- The integration of zenithal images captured by SUAS into GIS
- Adaptability of SUAS for sensors.

And in the light of observations that came to light during our research:

- Practicalities of SUAS operations aboard ships (mobilisation, deployment of equipment, harmonization of aircraft operations with shipboard operations)
- SUAS operations in regulated airspace
- Integration of non-zenithal imagery into GIS regarding shortcomings of consumer digital camera imagery when used for mensuration purposes.

We focus on practical issues: we believe the most valuable contribution we might offer the research community is feedback from our experiences as professional users of unmanned aircraft technology. This research is not based on an exhaustive knowledge review and aims to do no more than inform and guide those charged with management of HNS spills who might consider utilising present-day SUAS.

1) Airframe Review

<u>Fixed-Wing Aircraft</u>

It seems to us unlikely that a fleet of UAS equipped dedicated HNS spill response vessels will be maintained; if unmanned aircraft are to play a role in HNS spill response, deployment will be an issue. In which case, the complexity, purchase cost and cost of modification to the host vessel of launch/recovery equipment must be borne in mind when considering installation of a fixed-wing system. These costs may far outweigh the cost of the airframe.

Fixed-wing aircraft small enough not to require launch/recovery paraphernalia carry only small cameras and may not provide motion compensation for the camera. The degree of motion experienced by small fixed-wing airframes in maritime weather conditions may impact the utility of small aircraft for gathering zenithal data if, as we suspect, photogrammetric techniques cannot be used to compensate for raw image non-orthagonality.

Helicopters

The challenges to be overcome if unmanned helicopters are to be operated from ships are numerous. Apart from obvious deck safety issues, aircraft maintenance concerns, and the need for well trained crews; technological hurdles must be overcome. The helicopter would need to be capable of far more precise navigation during takeoff and landing than its terrestrial counterpart, to compensate for motion of the deck. Such a system would be of little interest to commercial SUAS operators, therefore it seems unlikely it would be produced in sufficient numbers to drive its cost below this project's target threshold.

Multi-Rotor SUAS

We chose to use a multi-rotor aircraft primarily for reasons of convenience; given the scope of the work and the budget of the project any other class of airframe would have been impractical. However, our results demonstrate the versatility of multi-rotor aircraft, which are limited in scope only by endurance and wind speed constraints. Moreover, in the ship-borne role they face none of the obvious launch and recovery issues of other classes of airframe.

Subject to tests in more realistic conditions than the benign weather we faced, there is no reason why multi-rotor aircraft should not be considered for maritime use. The amphibious multi-rotor airframe example and our own flotation accessory (see Figure 2.5) indicate marinisation of multi-rotor airframes is both feasible and practical.

Multi-Rotor airframes have become the prevalent choice for commercial SUAS operators, particularly those with photographic rather than surveying aspirations. The growing consumer market is driving development of this group of airframes at a surprising pace; we anticipate limitations noted previously, particularly endurance, are likely to become less severe in the near future.

Other types (lighter-than-air, flexible wing)

Lighter-than-air aircraft are unlikely on the grounds that systems small enough to be launched from and recovered from small ships would be not rugged enough to survive offshore; those large enough to carry reasonable sensor payloads would be too large to be manageable.

Flexible wing systems seem unlikely candidates for ship-borne deployment because tangled rigging and canopy inflation would be problematic on unstable, dynamic decks. Furthermore, if manned powered paraglider performance is taken as a guide, operational wind strength limits would preclude flight in all but the mildest offshore conditions. However, their relatively slow landing speed would endow such aircraft with a positive advantage over fixed-wing aircraft capable of carrying comparable payloads.

2) MEMS Sensor Autopilots in the Marine Environment

As noted previously, we justified probing autopilots independently of airframes by arguing that the current generation of low-cost SUAS autopilots employ inertial navigation sensors drawn from a common family of devices. The vulnerability of any one autopilot to a particular environmental factor would, with reasonable likelihood affect all autopilots, and since most autopilots can be fitted to any type of airframe, all airframes.

Our observations encompasses both autopilots and ground-stations.

- Sensor and Autopilot Calibration.
- Magnetometer errors.
- 'Home' location and Radio Control failsafes, and 'Follow-Me' systems.
- Ground station compatibility with HNSS tasks:
  - Problems of tiled-image backgrounds,
  - Waypoint file editing,
  - Navigation data log formats and Post-Processing,
  - Video downlink quality limitations.

Sensor and Autopilot Calibration

A concern we have regarding ship-board use of MEMS autopilots is sensor initialisation. Unlike mechanical gyroscopes that self-align by sensing the direction of gravity in a gradual process that can take several minutes, MEMS initialise in a fraction of a second. At the moment of calibration the aircraft must be stationary and, in many cases, level. Our third trial (see section 4.3) was planned primarily to explore sensor calibration on a pitching, rolling and heaving deck. The autopilot we used can be initialised in a non-level attitude, but must be stationary. We had in mind a workaround to cater for dynamic pitch and roll during calibration, but no plan for dealing with disruption due to heave. Any autopilot considered for Maritime use must be capable of being initialised under realistic ship-board conditions.

Magnetometer Errors

Until trials proved our fears groundless, we were also concerned with Magnetometer performance aboard ships. We anticipated two sources of errors: initial calibration and de-stabilisation of the aircraft during flight. The latter posed the greatest threat because spurious magnetic fields generated by ferrous structures or Electro-Magnetic radiation might result in sudden flight path deviations when the aircraft is most vulnerable, i.e. in close proximity to the ship's hull, or near elevated structures such as masts, antennae etc.

Variations in the earth's magnetic field occur naturally and lead to magnetometer errors when an aircraft is used at a site geographically removed from the site at which calibration was performed: it

is normal practice in these circumstances to re-calibrate the compass. Obviously, this is not an option if disturbances to earth's field are due to local ferrous structures. In order to operate at sites where magnetometer errors occur, our pilots take off with the aircraft under manual control (in which mode the compass minimally influences flight characteristics), climb carefully until telemetry indicates inclination and declination are within tolerance (i.e. match readings obtained when the compass was last calibrated), then engage full autopilot assistance. In our trials, we found this procedure to be unnecessary but the fact we had this procedure in mind, and had practiced it, shows how critical magnetometer performance is to this class of autopilot.

'Home' Location, Radio Control Failsafes and 'Follow-Me' systems

The problem we encountered with 'Range Error' is an idiosyncrasy of the MikroKopter autopilot but the notion of maximum working range is of prime importance to commercial SUAS operators. Most autopilots include programmable or firmware defined height and range limits, the scope of a mission must be known in advance and it must be compliant with autopilot limits.

Associated with the notion of maximum range is the concept of loss of radio control failsafe protocol; both relate to 'Home' location, usually geographic coordinates registered just before the start of a flight (some autopilots also allow the pilot to register the aircraft's current location as a new 'home' during flight). 'Fly-Home' can be manually commanded by the remote pilot, but crucially it is automatically triggered when the autopilot sense loss of radio communications with the pilot (in some systems, the ground station). This is a reasonable (and in some countries, mandatory) requirement, but as ship-board experiments on ship showed, a complex issue if 'home' is continuously on the move. In our opinion, a pre-requisite for any autopilot considered for ship-board use is provision of dynamic 'home' updates. A system akin to the MikroKopter 'Follow-Me' system, which continuously communicates its location to the aircraft, might serve as a possible prototype.

The problem of dynamic 'home' becomes even more significant with fixed-wing aircraft. Aircraft speed control is critical during the landing manoeuvre; SUAS are almost always under autopilot control during this phase of flight. However, the autopilot usually applies knowledge of the wind direction, runway alignment and runway threshold coordinates in order to plan a detailed approach path. The autopilot will calculate a height profile and time schedule that ensures the aircraft touches down with minimum airspeed. Clearly this strategy cannot apply to a continuously moving landing site (or arrester system); it seems unlikely that such a complex algorithm would be implemented in a low-cost autopilot.

Before we close this discussion of autopilot 'home', the dynamic 'home' location implemented by the MikroKopter's 'Follow-Me' system warrants further analysis in the context of tethering. According to the results of earlier trials, we had expected to show how the 'Follow-Me' system simplifies tethered flight: with the system in use the aircraft should actively maintain station above the beacon therefore the tether serves merely as a safety line, for example to prevent the aircraft inadvertently straying following navigation failure.

The use of a marine tethered platform, particularly if the tether functions as umbilical carrying power and sensor data communications, raises possibilities in the context of HNS spill management ranging from simply raising communications antennae to extend line of sight thus improve range to long-term surveillance.

Ground-Station compatibility with HNS spill data gathering tasks

Only autopilots capable of recording navigation data on board the aircraft, rather than in the ground station, should be considered for HNS spill management support aircraft. The simple autopilots likely to be encountered in low-cost SUAS are not dependent on connection to a ground station. Unlike their more sophisticated, longer range counterparts, SUAS are often flown without a ground station at all. Ground station telemetry links are not critical system components and usually comprise a low-powered radio system. In our experience ground station links are relatively unreliable and prone to temporary interruptions; when a continuous navigation record is critical, for example during a photogrammetry mission, an on-board data storage facility is essential.

A number of pre-and post-processing tasks necessitate manipulation of navigation data and waypoint parameters. Usually navigation files are in plain text format (often employing machine readable tags, or simple delimiters) and can be manipulated with simple text editor software. Typically we hand edit files in order to dissect master waypoint lists into individual flight plan files, or to parse and re-build a navigation files to re-organise data in formats compatible with photogrammetry programs. An autopilot/ground station without access to navigation and flight plan files will be difficult to work with.

We find a live video stream to be extremely useful, if not essential, for most SUAS tasks. Even orthophotograhy, which is often undertaken by 'throw and forget' pre-programmed fixed-wing aircraft, can be enhanced if camera function is monitored – for example to abort flight if the camera battery runs out. For surveillance and manual photographic tasks, live video is essential. Many (but not all) consumer digital still cameras provide a live-view output, however the nature of this signal must be understood if a suitable camera choice is to be made; the live video signal, which is an analog television signal, bears little relation to the format of data stored in camera media. For example, a PAL composite video frame comprises 576 usable (out of 625) lines. There is no standard horizontal resolution, however with the usual 4:3 aspect ratio a video frame approximates to a 780 x 580 pixel image. The quality of the camera's optics and sensitivity of its sensor impact picture quality, but it can never compare to definition of the video and stills stored on camera media.

Furthermore, equipment available to SUAS operators is limited in power and strength by national communications regulators. The ground station must incorporate a high gain receiver antennae (often automatically tracking the aircraft) if usable video feed is to be guaranteed. The use of a Composite Video to TCP/IP converter and transmission of imagery via wireless LAN, as we did in our dip experiment, is one possible solution to improve this aspect of point-to-point live-video feed.

In regard to point-to-point A/V equipment currently used by commercial UAS operators, distribution of the signal is possible through use of several receivers tuned to the same channel so that alternate monitor locations can be set up. In a ship-board scenario we can imagine a command centre on the bridge near the communications centre of the vessel whilst the SUAS crew, in order to retain line of sight with the aircraft, operate from an open deck using a second receiver and monitor. However, we think it unlikely many SUAS operators will have experience of rigging a ship in such a manner now will they have equipment to hand. If low-cost unmanned aircraft systems are to be considered for HNS spill support, particularly if rapid deployment to vessels-of-opportunity is envisaged, considerable thought must go into specifying equipment: standard commercial SUAS rigs do not lend themselves to ship-board deployment.

3) Practical Considerations

As noted, most low-cost SUAS autopilots will, by design, or to comply with Aviation regulations, execute failsafe flight home protocol following loss of Radio Control. The protocol usually includes a short period of grace during which aircraft loiters before commencing flight home; this allows the pilot a few seconds to re-position the radio-control transmitter in order to regain contact with the aircraft (assuming the aircraft has flown behind an obstacle due to a pilot command or a waypoint programming error)

On board ship, radio contact with the aircraft is most likely to be broken because the ship turns. Even if the pilot is aware of alternate vantage points, to reposition will probably require steps, ladders, and narrow passageways to be negotiated. In this case, it seems unlikely that the aircraft will loiter for long enough to prevent disruption of the mission. Clearly, communications between SUAS crew and ship's crew responsible for steering essential, but the ship might be forced to manoeuvre at any time.

A more robust system would be needed to ensure radio contact with the aircraft can be maintained at all time. For example, communications between the ship and the aircraft might be via a centrally-located transmitter with a clear field of view: local communications between the pilot and the master antenna might be via one or more short range repeater modules. Off-the-shelf data communications modules, such as those we used for aircraft telemetry, abound and many provide networking abilities; the suggestion to assemble a local network with two or three such devices is neither outlandish nor impractical.

The preceding paragraphs indicate that mobilisation of adapted terrestrial equipment on board a ship is a topic not to be taken lightly. But communications between SUAS crew and ship's crew is equally important. The ship's crew is unlikely to prioritise SUAS operations above all other activities but without a significant degree of understanding regarding the limitations of SUAS systems and the impact ships activity has on SUAS operations (for example how sudden turns result in loss of radio control ; the use of radio equipment that might jam SUAS signals; the length of time motion of ship

should be minimised when the SUAS is to be launched and recovered; headings to be avoided to prevent loss of radio control), SUAS operations would be jeopardised.

The notion of 'rapid response' is valid only if all members of the team; those handling SUAS and those handling vessel, are prepared to act in concert and this demands understanding each other's protocols. In a structured organisation such as the Navy, preparedness to rapidly assimilate an unusual activity might be expected. This attribute was clearly demonstrated by the structured and decisive manner in which the INS liaison officer assigned to the trial interacted with the ships command hierarchy in order to integrate SUAS missions with the ship's other procedures and activities. However, for successful deployment of SUAS on an opportunistic basis on merchant ships, those involved in mobilisation would need considerable mediation skills in addition to technical prowess.

The unusual combinations of circumstances encountered during the offshore trial (section 4.3) clearly illustrate the restrictive impact Aviation regulations can have on SUAS operations. It seems unlikely that a HNS spill response would be mounted without involving ATC, particularly at spill sites in controlled airspace. It should be noted that many major Irish port towns, Waterford, Cork, Limerick and the Shannon Estuary, Galway, Sligo and Dublin, all lie under controlled airspace. Therefore protocols to coordinate SUAS with other air traffic would be a real and critical aspect of HNS spill preparedness. Manned aircraft will almost certainly be part of a spill scenario; for SUAS to be safely and effectively integrated into the effort, crews may need advanced training such as aircraft radio communications licenses.

4) Adaptability of SUAS for sensors

The success of our dipping experiment (trial 4) clearly demonstrates the adaptability potential of SUAS, although our choice of aircraft considerably simplified matters. The sensor package was entirely self-contained, of similar weight and volume to the camera gimbal usually affixed to the aircraft, and of course the multi-rotor airframe is ideally suited to ad-hoc modification.

The use of wireless Network hardware allowed us to collect data from a number of sensor simultaneously, and because we could view data using standard computer applications (Microsoft Hyperterminal and Microsoft Internet Explorer), minimised the engineering overheads we faced implementing a data gathering system. Moreover, the communications link was duplex; we could have relatively easily remotely control the sensors via the Network.

We constrained ourselves to a LAN, but with the addition of standard off-the-shelf hardware could have accessed data via the Internet. Our illustration of the utility of the Internet (to disseminate data for real-time assessment by experts) was contrived, but based on a real need that came to light during background research.

Enquiries to locate a chemical sensor to trial in the project led to the manufacturer of a suitable hand-held probe, logging and display device. We were told that the logging device contained proprietary processing algorithms and its probe would not function unless connected to the device. The manufacturer suggested a workaround whereby we transmitted raw data via the Internet to a Web service they would provide where processing could take place. We would be given just enough information to remotely control the probe locally, but not allowed access to proprietary algorithms.

Whilst this example primarily concerns protection of Intellectual Property, it also illustrates another benefit of our network-based solution, that it permits processing overheads to be divided between the airborne platform and ground-based resources. For certain data gathering applications, perhaps where large quantities of data are involved, distributed solutions may offer significant advantages to stand-alone, self-contained sensor packages.

Finally, we should also point out that whilst our dipping experiment was intended to demonstrate remote sensing, without any modification to the aircraft we could have instead performed physical sampling. In a HNS spill scenario, the ability of a SUAS to collect water samples is probably a more useful attribute than being able to stream sensor data.

5) Integration of zenithal data from SUAS into GIS

The site of our Orthophotography trial was carefully chosen. The scene not only allows us to demonstrate the utility of the photogrammetric processes, but also to reveal two limitations of the process that may restrict its use over water. We do not believe observations discussed in following paragraphs are due to defects of the photogrammetic software employed (the suite developed by Marc Pierrot Deseilligny, available from the TAPENADE project Website, www.tapenade.gamsau.archi.fr/TAPEnADe); commercial aerial photogrammetric products we have encountered employ identical proc4essing strategies and would be equally constrained.

In order to integrate zenithal imagery into a GIS, to project it in the GIS's coordinate system, imagery must be orthorectified to remove scale, perspective and displacement errors and it must be georeferenced. Unless the camera's precise external orientation is known, both operations are tackled by means of photogrammetric processes that depend upon recognition of tie-points, invariant features that can be unambiguously differentiated in two or more adjacent images.

The foreshore scene we modelled includes both terrain and water. Although the final orthophoto mosaic shows clear detail over land, beyond the image breaks up beyond the shore. Black artefacts that are not natural features. Inspection of the sparse point cloud which maps tie-points in 3D (see Figure 4.4.3) reveals the source of the problem: tie-points cannot be generated from featureless images. The following view of part of the tie-point cloud illustrates the problem clearly. Only three tie-points were identified offshore, the barrel and two other objects. These can be seen in raw orthophotos.

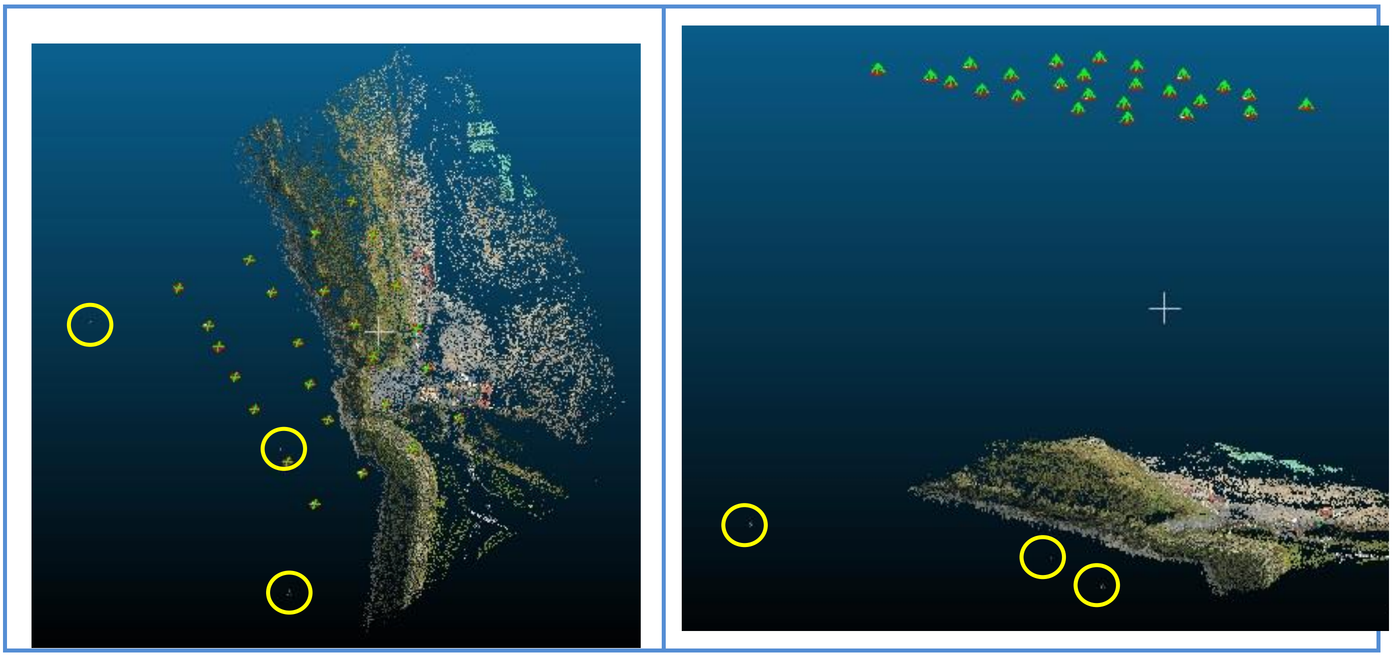


Figure 5.1 Views showing debris locations identified by tie-points

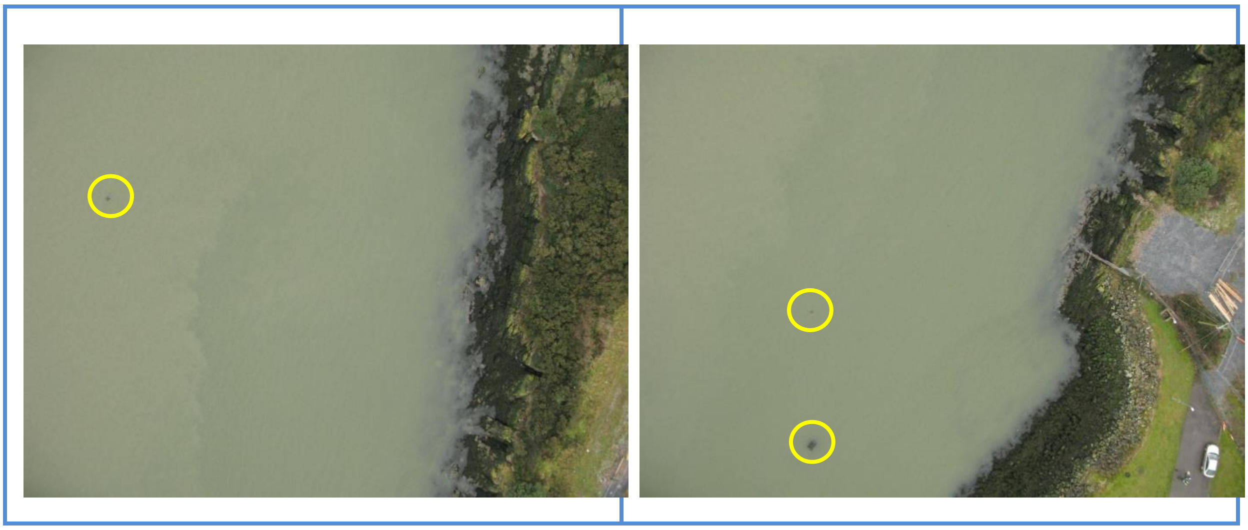


Figure 5.2 Raw orthophotos showing barrel (left) and other objects (right).

We believe the photogrammetric process will also fail to deal with wave-strewn scenes. In this case problems would arise from false tie-points. Recognisable features on waves might persist long enough to be captured on successive images and be recognised by the software, but would be in geographically different locations. The iterative triangulation process that determines camera location (so-called bundle adjustment) would fail.

The photogrammetric georeferencing process also depends on recognition of surface features, but used to associate the processes internal coordinate system with the external system in which location of features is known, rather than to link adjacent images. The accuracy of photogrammetric products is therefore proportional to the accuracy with which control point locations are known. Usually control point features are mapped with standard terrestrial surveying equipment, but on a contaminated site, such as that we contrived for Trial 4, human intervention is not desirable. If the orthophoto mosaic shown in Figure 4.4.5 were to be georeferenced, it would have had to be done by choosing natural features that could be identified on an existing map or georeferenced aerial imagery. Clearly, in featureless terrain, or areas without accurate geographic information, pre-surveyed control points would not be an option, the notion of rapid, totally remote-sense data gathering would not be possible.

Shortcomings of automatic tie-point generation algorithms we believe to underpin photogrammatic software currently used by commercial SUAS operators, poses a significant and possibly insurmountable hurdle to its use over water. However, given that over-water scenes lack relief, orthorectification may not be essential, particularly if imaging camera is carried in a high performance gimbal; stabilised brushless gimbals are now commonplace and provide unprecedented standards of motion compensation. Lens distortion needs to be corrected, but as we showed in Figure 4.4.4, in Atlantic areas served by EGNOS enhanced GPS, raw imagery can be

georeferenced with GPS data with reasonable accuracy. For tasks such as mapping algal blooms, this simple approach, perhaps in combination with tactics such as using a long-focus lens and capturing images from as great a height as possible, offers a viable alternative to the photogrammetric process.

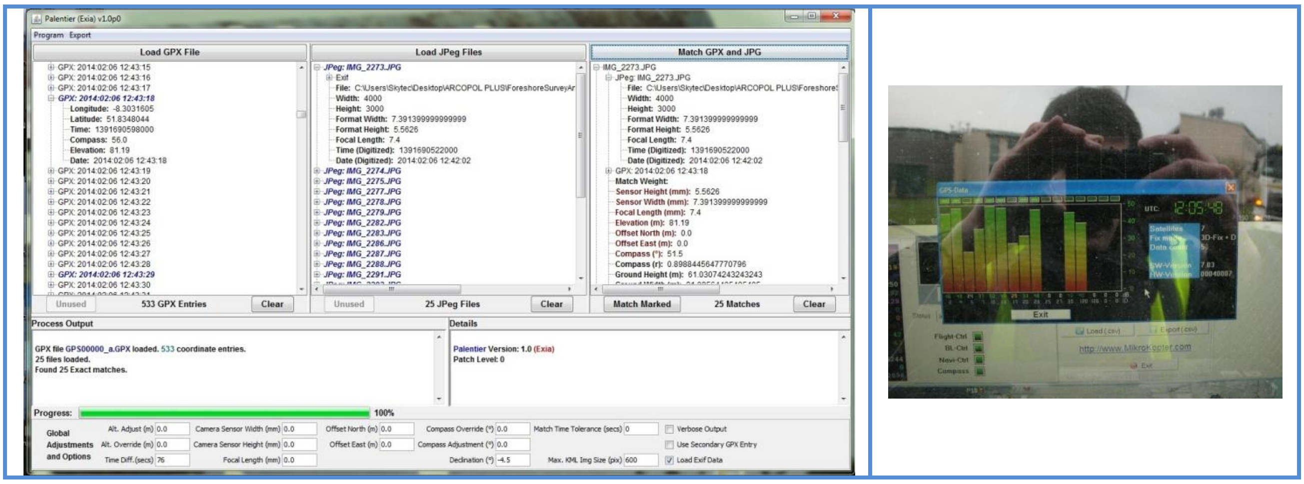


Figure 5.3 (Left) Screenshot of Open Source Palentier Software written be Mark Willis (www.palentier.com) used to prepare Figure 4.4.4. The software scales and rotates images using data extracted from the SUAS navigation data file and information stored in the header of raw images. **(Right)** Matching GPS time to image time by photographing the aircraft's GPS telemetry feed. The image's time-stamp reveals a 76 second difference between camera time and GPS time.

6) Uses of non-zenithal imagery: integration into GIS and metrics

Marc Deseilligny's photogrammety software suite is unusual in that it provides a number of options that allow a range of tasks to be tackled. Apart from orthophotomosaic and DTM production, it is also possible to generate dense point clouds (and from them 3D geometries) of discrete objects (buildings, archaeological artefacts) or small areas of terrain. The following point cloud was generated from a key image and a cluster of eight supportive images selected from one flight.

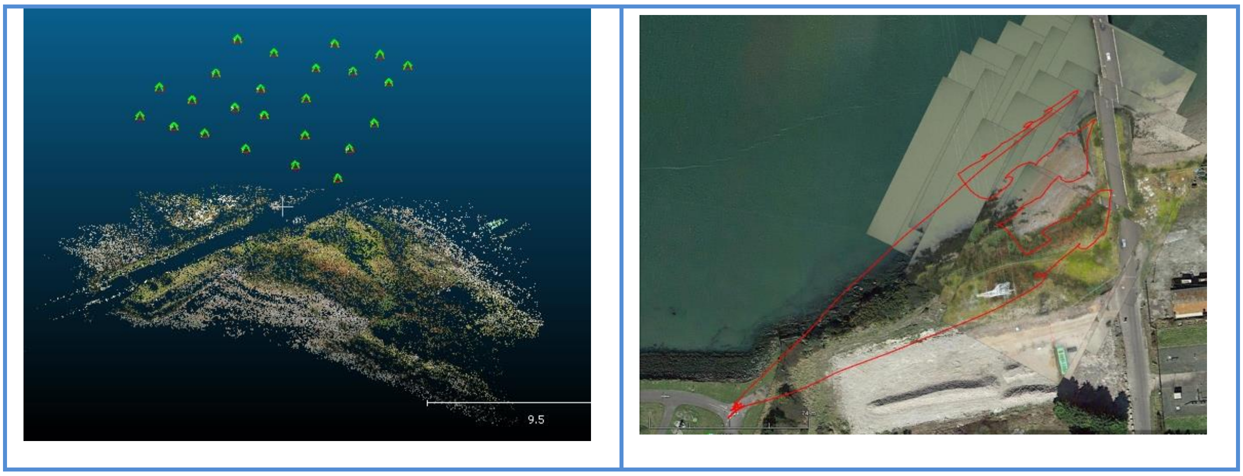


Figure 5.4 Sparse Point Cloud showing tie-points (Left); Ground track and scaled rotated and roughly georeferenced orthophotos (Right).

Figure 5.5 Alternate views of the dense point cloud: note ‘mountainous’ appearance of water, spurious points due to lack of depth information.

As with the previous examples; if geographic information is known about the site (either natural or surveyed-in control points can be identified in the images) 3D products derived from this point cloud could be integrated into a GIS. Alignment of the point cloud with a geographic coordinate system simply involves an additional step in the bundle adjustment process to fine tune the data which otherwise is relative only to camera internal dimensions. The principal reason to georeference dense point clouds (and by extension 3D products derived from them, such as 3D geometries from which volume measurements can be taken) would be allow 3D information to be added to the underlying database – assuming the GIS implements a suitable 3D viewer. Distortions inherent in raw imagery that result invalidate direct measurement-taking, can be overcome by intimate photogrammetry, although accurate scaling is a problem unless references in the scene are available.

In regard to HNS spill response, we envisage detailed photogrammetry being useful for wreck and debris modelling in which case the problems of false tie-point generation might be overcome by masking water from source images

7) Non-zenithal imagery: integration into GIS and metrics

The following images illustrate the limitations of untreated imagery typical of a SUAS carrying a consumer digital camera.

Figure 5.6 Hovering only a few metres from the barrel, low enough for downwash from the propellers to ripple the water's surface.

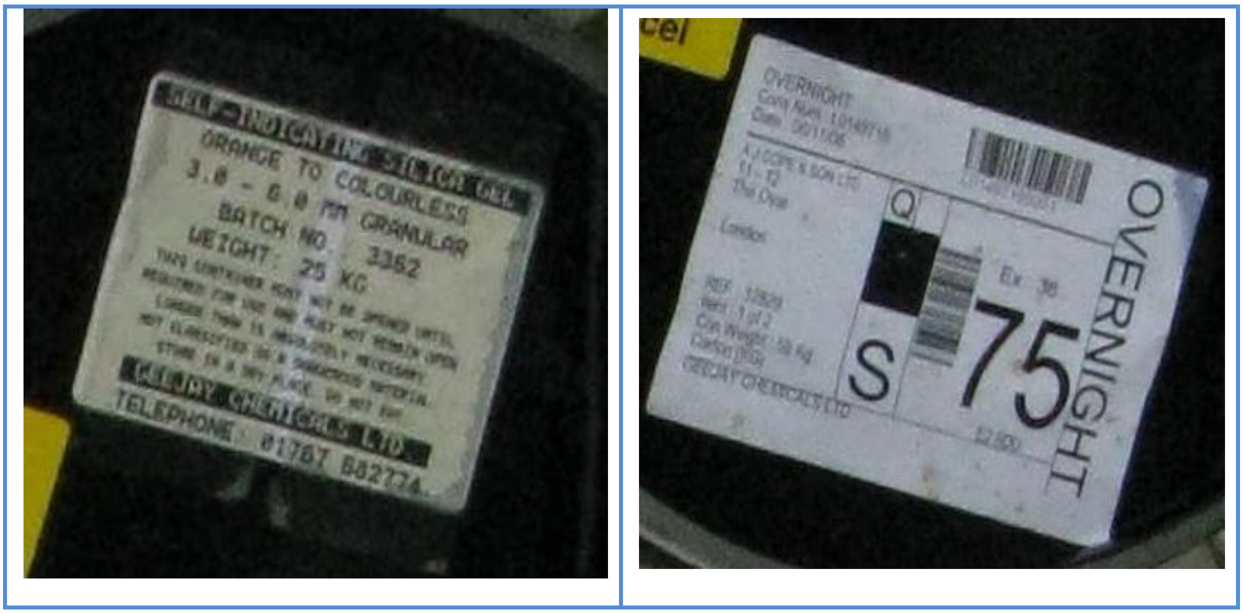


Figure 5.7. Millimetric pixel resolution, yet print remains illegible.

Figure 5.8 How reliable are the colours of these labels? Ambient light colour temperature and the colour of light reflected from water influence perceived colours.

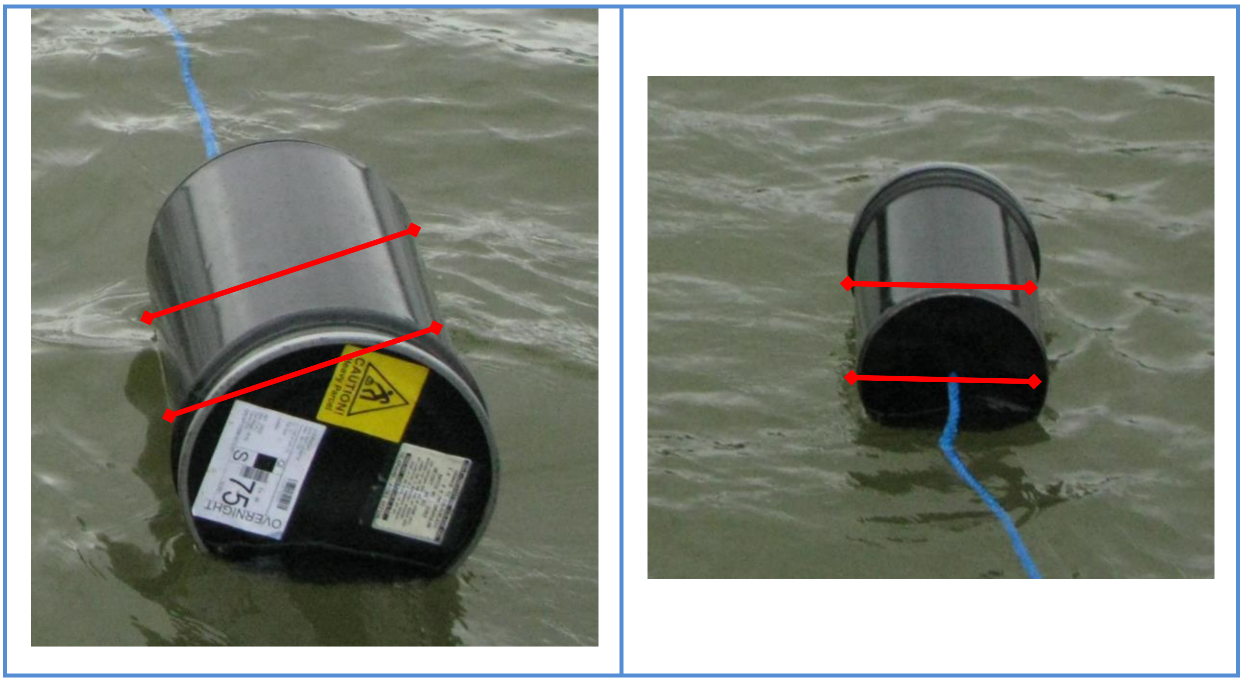


Figure 5.9 Scale error: Scale ambiguity cannot be resolved from raw images. Both red lines in each image are identical in length yet in the left image the base of the drum appears slightly narrower than the top (the drum is cylindrical). Lens focal length, distance from the object and viewing angle contribute to the illusion.

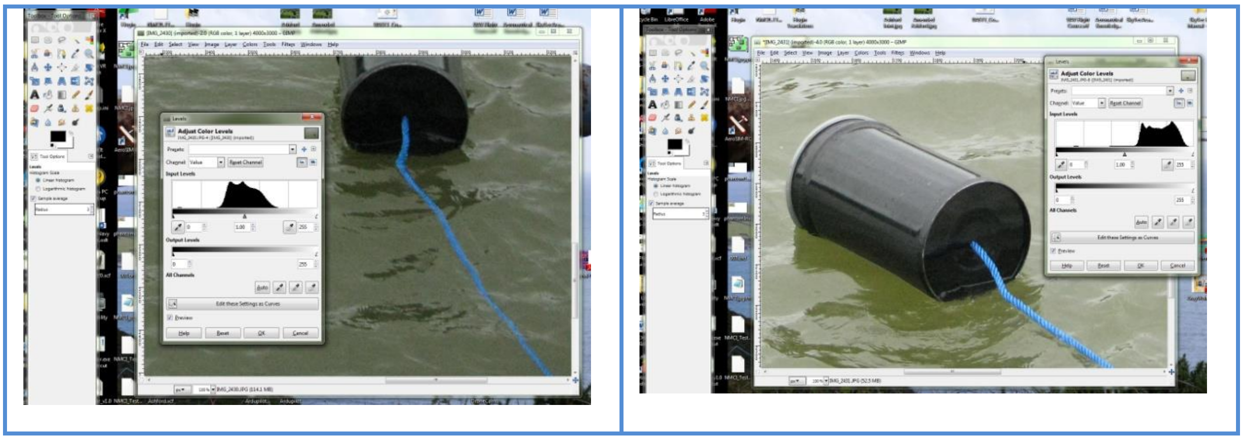


Figure 5.10 Exposure control: Depending on camera setting, automatic exposure may hide details. The left-hand image's histograms indicate 'correct' exposure numbers of light and dark pixels are evenly distributed about the 'average' grey level. Manual control of exposure was used to purposely overexpose the right-hand image in order to reveal detail in the base of the drum.

Figure 5.11 Base of the barrel revealed.

Integration of oblique imagery into a GIS would be simple, using the technique previously outlined to match GPS time with time-stamp on image headers.

6 Conclusions

Readers unfamiliar with the capabilities of state-of-the-art unmanned aircraft technology may be impressed by the versatility of our aircraft, the diversity of data we produced and the confidence with which we tackled trials. Perhaps restrictions arising from ATC interaction, and our observations regarding practical integration of unmanned aircraft systems into ship-board operations, also provided food for thought.

But to leave readers under the impression that current generation SUAS technology is ready to be pressed into service for HNS spill response would be misleading. We believe a number of challenges must be overcome before systems can be realistically integrated into spill response programmes.

If spill response data end-users are to benefit from the undeniable potential afforded by SUAS technology hinted at by results of trials such as ours, not only will specialised task-centric platforms need to be developed, but also strategies devised to place this technology in the hands of spill response agents and to train operators to harness its capabilities.

Technological Hurdles to be Overcome

Our failure to identify a suitable airframe for ship-board use within the target price-band shaped subsequent work on this project and denied us the opportunity to explore this topic in more detail. Clearly, airframe 'marinisation', particularly problems of launch and recovery, are key issues that further work on specialised pollution response sensor platforms should address.

In hindsight our autopilot investigation strategy appears overcautious, but lack of meaningful findings (particularly in regard to equipment limitations) is only to be expected given the atypically benign weather conditions we contended with. Our success at operating a MEMS equipped autopilot should not be taken as justification to cease research into this topic. A thorough, objective, exploration of MEMS equipped autopilot performance in the vicinity of vessels might prove to be of significant value to future aircraft users of and designers of maritime SUAS, given the significant growth of civil and military UAS activity universally predicted by industry pundits.

We perceive SUAS to be specialised tools, akin to electronic test equipment used by specialist repair technicians; without training and a degree of expert knowledge, systems are unusable. Mainstream robotics researchers seem to share this view; much work in this field is targeted at automating technology in order to make it accessible to lay people. UAS autonomy is a reasonable proposition only in certain circumstances; in a dynamic emergency response scenario, in which multiple factors vie for dominance whenever decisions are to be made, it is hard to imagine a (low-cost) pre-programmed, 'launch and forget' UAS with sufficient intelligence to successfully mimic human operators. The goals of robotics research are therefore at odds with what we believe to be key requirements for effective pollution support unmanned aircraft technology. We believe human-machine interaction to be essential for search, exploration and inspection tasks; humans supported

by task-centric interfaces that provide an ergonomic balance between aircraft autonomy and manual control. This aspect of SUAS development seems to us to present a particularly rich vein of research potential.

Arcopol project specifications refer only to zenithal pictures; this focus is reasonable given that currently the only data for which there is demand from commercial SUAS service customers comprises imagery captured with visible-light consumer digital cameras (also to a limited extent NIR converted digital cameras, and to an even smaller extent thermal imaging cameras). This situation reflects an apparent lack of interest from industry for services that demand task-centric sensor platforms. But if pollution monitoring tasks necessitate development of specialist equipment, how will that equipment reach the market? Without current or historical evidence of demand from industry for data products facilitated by specialist equipment, will researchers be motivated to commercialize their ideas in the civilian market?

If this analysis proves to be accurate and pollution response policy makers find attempts to adopt SUAS technology thwarted by high costs or lack of suitable equipment, one possible solution might be to borrow from the Open Source model already prevalent in the SUAS products market. Devices such as autopilots and camera gimbal controllers, developed by consortia, are priced only to cover the costs of their manufacture. Product (particularly firmware) development is contributed freely by collaborators. Development of HNS spill response sensor platform packages, targeted exclusively at state and semi-state agencies, might be undertaken by research projects with only materials and manufacturing costs for end users to bear. Systems would be far more affordable than those produced by the conventional free-market consumer model. Lower costs might encourage take-up of technology by state and semi-state agencies that might otherwise not consider SUAS because military systems are too expensive and affordable civilian systems inadequate.

The commercialization dimension of SUAS research is one, we believe, worthy of business analysis. We suspect the standard consumer behaviour model fails to take into account key features of the evolving SUAS professional user community therefore popular expectations regarding the evolution of low-cost versatile sensor platforms may be in misguided.

As noted in previous paragraphs, currently the market for civilian commercial SUAS services is centred on imagery products therefore the only type of payload commercial operators are concerned with are cameras; sensor integration is a topic of less interest. Further research along the lines we initiated with our multi-sensor adaption might be particularly beneficial to developers of a HNS spill response sensor package a) because low-cost sensor integration is clearly a key issue, and b) because for reasons noted previously spin-offs from commercialization research unlikely due to small size of market for HNS spill monitoring equipment.

Deployment Issues

The path from SUAS procurement budget approval to the placement of data-gathering assets in pollution response agents' inventories is likely to be far from direct. Fundamental questions must be asked before plans to integrate SUAS data-gathering into pollution response workflow can be laid, such as whether equipment should be operated by state body, semi-state body, or our out-sourced to a private contractor; and the exact specifications for data acquisition deliverables.

Research into these questions should not be deferred. Such is the rapid pace of recent SUAS development that surely it is only a matter of time before low-cost, marinised, airframes and suitable sensors become available; pollution response policy makers should be in a position to harness this technology without delay.

Spill Support Task Classification and Crew Appointment

During our experiments we applied a number of disparate techniques and demonstrated a range of skills. Exploratory missions required dexterity, practice and crew cooperation; planning surveying tasks required intimate knowledge of post-processing techniques; ship-board tasks required familiarity with the vessel's chain of command and operational procedures. We believe our experiences to be representative therefore others who wish to replicate these tasks would require specialist training. In order to integrate a SUAS into a pollution response scheme, data-gathering tasks must be catalogued and subsequently a training syllabus developed; and minimums experience credentials for crews established (for example civilian SUAS crew members deployed to ships might be required to hold 'Personal Offshore Survival Technique' qualifications).

Crewing Policies

An agency responsible for HNS spill response must consider a number of factors before deciding whether to crew an SUAS with its own personnel or to enlist external support.

In Ireland, the UK and soon in Spain, operation of SUAS is restricted to organisations that are approved by National Aviation Regulators. If Spain follows the Irish/UK model, pilots must belong to (or own) an approved SUAS venture, and may fly only the type of aircraft which they are trained to operate and for which the organisation has been approved. The organisation's documentation must also describes the company's scope, safety policies, and operating protocols.

The bureaucracy that accompanies SUAS operation approval is not complex but is tightly focussed in a field probably alien to non-aviation related state and semi-state agencies. These alien concepts, in combination with administrative burdens, and logistical problems (recruiting pilots, maintaining crew experience levels, maintaining aircraft; administering day-to-day SUAS operations and liaising with the NAA) may complicate the matter to the extent that even choice of an appropriate department within the agency to take responsibility for the SUAS becomes troublesome.

Even if NAA regulations do not demand such a detailed degree of organisation, as might be the case in Portugal, such are risks to third parties from operations at emergency response sites, and need for accountability, that a responsible agency might consider adopting a similar model.

If in-house solution presents too great an administrative burden, out-sourcing SUAS services to an established commercial operator might be considered, but in this case quality assurance must be addressed. As noted previously, currently commercial SUAS operators are generally small companies with limited resources. A contractor for emergency response must be able to commit sufficient staff and resources to guarantee adequate call-out response and maintain adequate personnel levels during a prolonged incident response.

Utilization: Factoring in Regulations

The unusual combination of circumstances encountered during our trials allowed us to illustrate, with first-hand accounts, the impact airspace regulations can have on SUAS operations.

Readers might suppose that airspace rules applicable to everyday SUAS operations would not be imposed in the event of serious pollution incidents. This indeed is the case; however airspace restrictions in segregated airspace might be more stringent than those imposed elsewhere and would be policed more thoroughly. Risks of collisions between unmanned and manned aircraft in areas in which aircraft are being flown lower than usual by task-focussed crews are bound to be of concern to aviation regulators. Restrictions to SUAS usage in an emergency response zone might be surmountable; for example negotiations with National Airspace Authorities might be based on the premise that only pilots licensed to use Aviation radios and able to coordinate with manned aircraft and air traffic controllers will fly the SUAS, and the aircraft will carry a radar transponder.

Given the central roles ports, harbours and airports play in infrastructure, and that often all lie in close geographical proximity, the manner in which National Airspace Authorities intent to integrate SUAS into airspace during pollution incidents should be of concern to all Arcopol partners. Currently three of the four countries comprising the Atlantic Borders Region either have SUAS regulations in place or plan to introduce regulations. In these countries SUAS operators must comply with restrictions in the manner outlined previously. Although Portugal has not regulated everyday SUAS activity, one cannot assume that in an emergency response situation temporary restrictions would not be imposed. In our experience Aviation Authorities tread carefully with slow, measured steps: proposals to integrate SUAS operations in emergency response schemes cannot be introduced soon enough.

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APPENDIX 1 Bibliography

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APPENDIX 2 SkyTec Ireland: A Company Profile

	
Steve Slade - Operations Director A professional helicopter pilot for over 35 years, with a career that spans Military Aviation (including membership of the Blue Eagles Helicopter Display Team), the North Sea Oil and Gas Industry, and Aviation Consultancy. Retired from aviation in 2010 to launch SkyTec Ireland.	**Mike Griew - Technical Director** Graduated from the University of London in 1981 with BSc degree in Electronics Engineering. After working for five years as a Marine Geophysics engineer, launched a 23 year career in Aviation but maintained a practical interest in electronics, particularly embedded systems and human-computer interfaces. Resumed academic studies in 2001 and was awarded an MSc degree (Computers in Commerce and Industry) by the Open University in 2008. Changed tack again in 2010 to pursue a career in the Unmanned Aircraft Industry.

SkyTec Ireland was amongst the first SUAS service providers to gain Irish Aviation Authority approval to operate commercially (July 2012). In addition to general SUAS services and consultancy we now own and manage Irelands only IAA Unmanned Aircraft Registered Training Facility. The SkyTec Academy provides ground and flight instruction to aspiring Irish commercial SUAS operators.

In four years of commercial operations we have tackled a wide range of inspection, survey and videography tasks and boast a number of firsts including the first live TV video broadcast from an SUAS in Ireland (Ireland AM, November 2013) and the first lit gas flare inspection in Ireland (Whitegate Oil Refinery, July 2103); We have worked closely with UCC and the INS on a number of projects.

The company's co-directors are both highly experienced helicopter pilots with aviation management experience whose collective careers span over 60 year.