Unmanned Aerial Vehicle as Communication Relay for Autonomous Underwater Vehicle – Field Tests

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***Abstract*—This paper describes field experiments with an X8 Unmanned Aerial Vehicle (UAV) operating as a wireless communication relay while loitering over a REMUS 100 Autonomous Underwater Vehicle (AUV) being at the ocean surface. The paper describes the design of the communication relay payload, network configuration, optimal flight conditions and UAV antenna mounting, and experimental results. Experiments were conducted under less than ideal conditions with rain and turbulent winds leading to unfavorable roll and pitch motions of the UAV, and small waves surrounding the AUV. The results with data download from the AUV through the UAV communication relay to a ground station shows that at the tested (typical) flight conditions the distance and attitude between the AUV and UAV are not the bottlenecks in the communication network. The main bottleneck was identified as the capacity of the proprietary wireless system on the REMUS 100 AUV which was not specified as a high capacity data link, and seems to be set up by the AUV system manufacturer to provide a relatively low capacity, but very robust, wireless data link regardless of signal strength and quality.**

***Index Terms*—Autonomous Underwater Vehicle; Unmanned Aerial Vehicle; Wireless Communication**

I. INTRODUCTION

Buoys, Autonomous Underwater Vehicles (AUVs) at the surface, small Unmanned Surface Vessels (USVs), and other assets, operate with extensive data acquisition capability at the sea surface. In many applications, it is desirable to have fast (or real-time) transmission of the data to command and control stations in operations centers onshore or in mother-ships. Examples are surveillance, inspection and monitoring missions where operator interaction is needed to analyze the data, get situation awareness, make decisions, and execute tasks based on analysis of the data, see e.g. [10], [18]. Applications could be oil spill response, iceberg detection, environmental monitoring, scientific data acquisition, and protection or borders or areas.

The mentioned Wireless Sensor Networks (WSNs) operating at the sea surface have generally poor conditions for transmission of radio signals to other assets that are at the sea surface, near sea level, or at low altitude onshore. Reasons for that are microwaves propagation related phenomenon. High frequency signals requires Line-of-Sight (LOS) which on longer distances is disturbed by the Earth curvature and affected by first Fresnel zone requirements [22]. Moreover, signal reflections as well as changes in pressure and temperature in Atmospheric Boundary Layer (ABL) directly influence waves characteristic and propagation paths which effect in fading. Considering marine environment, it has been proved that sea state - both wave height and frequency - has direct influence on the fading effect [19]. Even sea breeze has significant effect on LOS communication [21].

The mentioned effects are in particular a problem for long distance communication (beyond a few hundred meters or a few kilometers). While one solution is to move AUVs, USVs or mother ships closer in order to improve the radio channel, this will in many cases lead to waste of time and resources such as fuel since the vehicles may have to move long distances to achieve this.

The use of a satellite communication link is a common approach, but it has its limitations due to only partial satellite coverage by most systems with small footprint, as well as relatively high costs and relatively low data rate. On the other hand, the use of elevated communication relays greatly improves the radio communication channel, but requires an elevated platform to provide sufficient position. While mountains, tall masts and aerostats may provide the necessary means onshore or on a larger mother-ship, another elevated platform is needed at the location of the data node at the open ocean surface. In this paper we study the use of small Unmanned Aerial Vehicles (UAVs) for this purpose, through field testing with a commercially available AUV and an Unmanned Aerial System (UAS) with a dedicated communication relay payload.

Multivehicle operations with coordination and data re-

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laying between unmanned vehicles is widely covered by the literature. Researchers work is multidisciplinary and focuses on different areas. Maximizing data transfer and range by refining UAV's path planning and nodes positioning has a notable place in the literature as well. Various experiments, based on different optimization methods, can be found, i.e. Field Gradients [8], Particle Swarm Optimization (PSO) in [14], Dual Ascent algorithm & modified Bellman-Ford algorithm [6], Model Predictive Control (MPC) [12], [13]. Moreover, communication capabilities can be increased with other methods, i.e. by vehicle-based antenna arrays [5]. Networking matters of Small UAVs - including usage scenarios and network architectures - has been described in [11]. Among others, problems of signal relying are also described in [20]. Directly, cooperation of UAV relaying signal from AUVs to the vessel has been tested and described in [15]. State-of-the-art solutions in multivehicle missions - including common C4 software, common navigation and path planning environments as well as Delay-Tolerant Networking (DTN) technologies - can be found in [18].

The primary purposes and main novel contributions of this research are to:

- Establish field experience with communication relaying between the NTNU owned and operated AUV REMUS 100 (at the ocean surface) and the UAV X8 (loitering above the AUV) using IEEE 802.11b/g (WiFi) wireless communication.
- Investigate the effects of UAV loitering altitude and radius on the communication quality.
- Investigate the effects of UAV pitch/roll motions due to turbulence and unsteady winds.
- Investigate the effects of AUV motions in ocean waves.

Key technical aspects are communication network architecture and choice of antennas and their location on the UAV.

II. UAV and AUV Communication Relaying

In this research, we set up and test data transfer between two end nodes, where at one end there is a REMUS 100 AUV with a IEEE802.11g or IEEE802.11b WiFi modem with some kind of antenna built into the top fin of the AUV, and at the other end there is the AUV Command and Control PC with standard WiFi and wired Ethernet connections.

Off-the-shelf wireless network systems have well developed mechanisms and protocols for data relaying. We have chosen to build the communication relay network using the following components

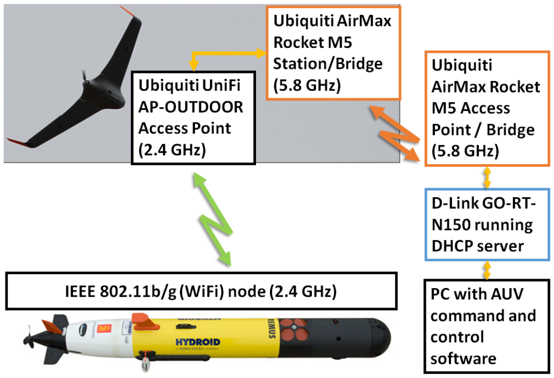

Fig. 1. Communication network architecture illustrating the main network components in the AUV, UAV and ground station.

- An Ubiquiti UniFi AP-OUTDOOR wireless radio modem is configured as an access point in the UAV to communicate with the REMUS 100 AUV WiFi modem. This access point operates at the 2.4 GHz band, has two antennas, uses the IEEE 802.11n/g/b protocol. It is configured as a transparent bridge to the network connecting the UAV and the ground station. As outdoor rated, the access point can work in temperatures between -30 to 75 °C in 5-95% condensing humidity. Device is powered by Passive Power over Ethernet (12-24V) and has maximum power consumption of 4.6W. Maximum provided transmission power is 27 dBm [3]. The access point is equipped with two supplied 5 dBi omni antennas mounted on the UAV.
- An Ubiquiti AirMax Rocket M5 is configured as a station/bridge in the UAV, with a wireless link to an access point at the ground station. Additionally, it is connected by wired Ethernet connection to the UniFi AP-OUTDOOR wireless radio modem. The radio is available in 6 frequency bands [1]. Because of frequency licensing and available bandwidth, a 5.8GHz Industrial, Scientific and Medical (ISM) [9] band has been chosen for the experiment. As transmission protocol Ubiquiti proprietary AirMax has been used. The AirMax, designed for outdoor use, is based - similarly to WiMax - on Time Division Multiple Access (TDMA). The protocol uses "smart polling" which predicts voice/data requirements and allocates sufficient bandwidth. Another feature is priority of active clients over idle ones [4]. The radio has two antennas for 2x2 MIMO mounted on the UAV: 3 dbi omni antennas of type WiMo 18720.3H, with a vertical beam of about 17 deg. Similarly to UniFi AP-OUTDOOR, the Rocket M5 can work in temperatures between -30 to 75 °C in 5-95% condensing humidity. Device is powered by Passive Power over Ethernet (12-24V). Maximum power consumption is higher

and can reach 8W. Maximum provided transmission power is 27 dBm [2].

- An Ubiquiti AirMax Rocket M5 is configured as an access point with bridge functionality at the ground station. The radio has two antennas for 2x2 MIMO mounted on a tripod at the ground station: 10 dBi omni antennas of type WiMo GP5000-10, with a vertical beam of 17 deg.
- A D-Link GO-RT-N150 router is connected to the AirMax Rocket M5 at the ground station in order to provide routing and DHCP service to the network. DHCP server is required by REMUS 100 WiFi settings. As UniFi AP-OUTDOOR cannot provide DHCP server and Rocket M5 is not able run such service in bridge mode the additional device was necessary.

The total system is illustrated in Figure 1. The figure does not show the communication required for UAV flight control, which includes another standard 2.4 GHz remote control (RC) and optional 433 MHz telemetry links. The RC-radiolink uses frequency hopping and was carefully tested during pre-flight for interference with the 2.4 GHz WiFi radio in the UAV payload, without any issues.

III. OPTIMAL UAV LOITERING AND ANTENNA LOCATION

The two antennas connected to the Ubiquiti UniFi (WiFi) link on the UAV should be mounted such that they have a suitable angle for the vertical beam of at least one of them to be pointed towards the AUV, while the UAV is loitering over the AUV being at the sea surface. The bank angle of the UAV depends on the radius of the loitering circle, and thus the antenna beam can be optimized by selecting the UAV loitering circle radius and altitude, for a given air-speed and antenna location. The use of two antennas means that e.g. one can be optimally located for clockwise loitering while the other is optimally located for counter-clockwise loitering. On the other hand, because the 2x2 MIMO radio can efficiently utilize both antennas at the same time, intermediate angles might in fact given even better results than single-antenna optimized operating conditions if it is know a priori that the UAV will always turn either clockwise or counter-clockwise.

An illustration with UAV antenna angles relative to AUV antenna is show in Figure 2. From the geometry it follows that the optimal UAV single antenna flight conditions are

$$\frac{h}{r} = \tan(\theta \pm \gamma) \tag{1}$$

In this equation θ is the UAV bank angle, and γ is the lateral tilt angle between the antenna mounting axis and the vertical axis of the UAV. It is assumed that two antennas are symmetrically mounted on each side of the fuselage as illustrated in Figure 2. Let α be the angle between UAV and AUV when both have no roll, i.e. $\tan(\alpha) = h/r$, where h is the UAV loitering altitude, and r is the UAV loitering radius. Eq. (2) can be equivalently written

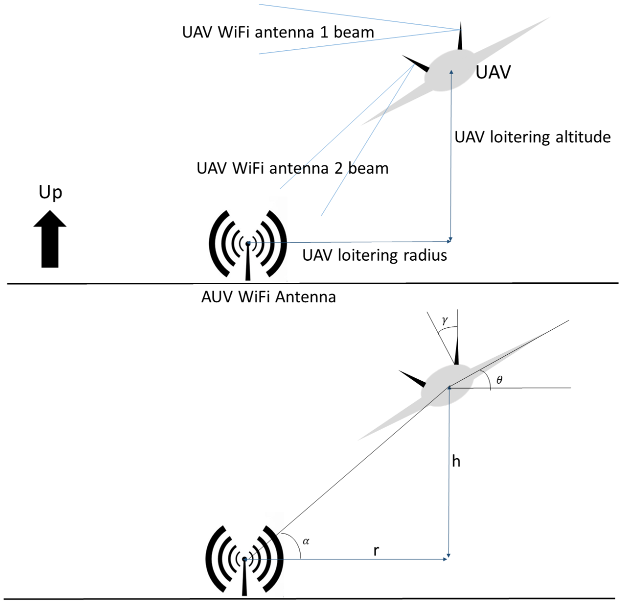

Fig. 2. Illustration of UAV antenna beams relative to UAV bank angle and loitering altitude and radius, during a banked turn.

$$\alpha = \theta \pm \gamma \tag{2}$$

Flight testing onshore was conducted to verify the suitability of the location of the antennas on the UAV, see Figure 3, for typical loitering radii and altitudes.

A standard formula for banked turn of aircraft is [7]

$$\tan(\theta) = \frac{v^2}{rg} \tag{3}$$

where v is the true airspeed and g is the acceleration of gravity. The X8 operates typically at $v = 18\ m/s$, leading to typical values given in Table I. For loitering radii in the range 50-150 m the optimal altitude is 61-87 m with antennas tilted 18°. From the extent of these two ranges, we notice that accurate control of the loitering altitude is more important than accurate control of the radius.

We also notice from Table I that for larger loitering radii there is only one optimal altitude (since one is negative according to (1), and therefore infeasible), while for smaller loitering radii both antennas can be fully effective and there are two optimal altitudes. The most favorable one would be the lowest altitude due to the limited vertical beam of the unknown antenna in the AUV

Radius r	Bank angle θ	Antenna tilt γ	No-roll angle α	Optimal altitudes h
50 m	33°	18°	51°, 15°	61 m, 13 m
100 m	18°	18°	36°	73 m
150 m	12°	18°	30°	87 m

TABLE I
EXAMPLE OF OPTIMAL ALTITUDE CALCULATIONS UNDER STEADY-STATE BANK ANGLE AND AIRSPEED ($v = 18\ m/s$) CONDITIONS, FOR ANTENNAS TILTED 18° LATERALLY FROM THE VERTICAL UAV BODY AXIS.

Fig. 3. Picture of X8 UAV with location of antennas used in the field test. The two white antennas are the 2.4 GHz WiFi antennas, while the others are two 5.8 GHz antennas for the AirMax wireless UAV-to-ground station data link, and one 433 MHz antenna for the UAV telemetry.

top fin (which is likely an omni antenna). Unfortunately, this low altitude gives small safety margins and is typically not an option. It can be observed that while a smaller antenna tilt angle seems favorable in this respect, one also needs to consider the vertical beam of the antenna mounted on the UAV and the magnitude of dynamic roll motion and bank angles due to turbulence and unsteady winds. A more detailed analysis should also consider the effect of pitch versus the longitudinal tilt angle of the UAV antennas, as well as the vertical beam of the AUV antenna and the AUV roll and pitch motions due to waves.

A similar geometric analysis can be made regarding the location of the 5.8 GHz antennas for the broadband wireless link between the UAV and the ground station. A good compromise for typical bank angles of 10-40° are found to be one antenna one each side of the fuselage, each tilted laterally about 10-20°.

IV. UAV PAYLOAD IMPLEMENTATION

To perform the experiment a dedicated payload - fitting Skywalker X8 platform requirements - has been developed. Its main elements are: Ubiquiti Rocket M5, Ubiquiti UniFi AP-OUTDOOR and Power Board. To increase payload capabilities it has been equipped with NetBurner SBL2E Serial-over-Ethernet adapter. Autonomous flight capabilities of the X8 UAV is provided by an ArduPilot autopilot. By default ArduPilot uses 433 MHz 3DR Radio Telemetry Kit. However to extend the telemetry range and reliability, as well as to limit number of transmitting units onboard, the Serial-over-Ethernet device has been used. Its input is connected to ArduPilot's telemetry port (TTL standard). Output on the other hand is linked with UniFi AP-OUTDOOR secondary Ethernet port. The Power Board provides necessary voltage levels (3.3V@3A, 5V@3A, battery level) and power connectors to all receivers. Due to flight-safety reasons the payload has been powered by an independent battery pack. All components has been attached to a dedicated frame, created using rapid prototyping 3D printer. As factory casings have been removed all devices were covered with protection coating layer. To keep aircraft's Center of Gravity (CG) within allowed limits payload layout has been carefully arranged and mounted in the central part of a fuselage.

V. TEST RESULTS

Fig. 4. Field tests at Hopavågen, Agdenes, Norway. The AUV is slowly drifting at the ocean surface, while the UAV is loitering above.

Field tests were conducted at Hopavågen in Agdenes, Norway, on 15th May 2014, with temperature about $8°C$, rain, sea state 1-2 (calm to smooth with typical wave heights about 10 cm), and winds about 10 knots with wind gusts up to about 20 knots. The flight tests were conducted within visual line of sight (VLOS) of the UAV pilot and radio communication, see Figure 4.

A. Flight data

Due to the challenging unsteady wind conditions, the UAV was operated on RC (manual remote control) during the tests. Figure 5 shows roll and pitch angles during the loitering. The mean roll angle is about 30° with 2σ (two standard deviations) values are about $+15°$ and $-80°$ roll angles. Similarly the 2σ values of pitch angles are about $-20°$ and $+25°$.

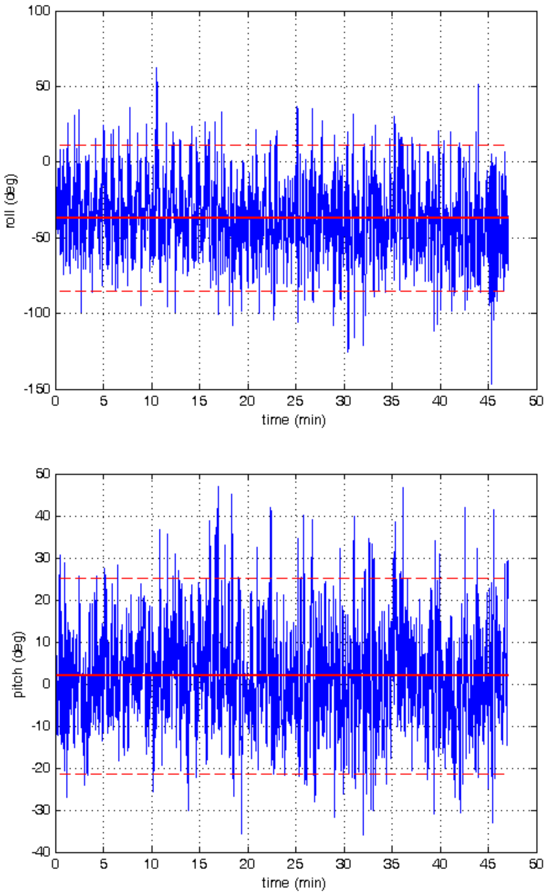

Fig. 5. Roll and pitch angles during loitering. The solid straight lines represent mean values, while the dashed lines represent 2σ (two standard deviations).

B. Reference tests

Reference tests were conducted at Breivika in Agdenes on the same day for the following conditions:

- Exactly the same setup as during field tests, excepts that all radio equipment is located in a small area close to each other with no motion, and at suitable antenna attitudes such that path loss due to distance, vehicle motions, ocean waves, etc. are excluded. This is marked as Test 3 in Table II.
- The PC with AUV command and control was connected via WiFi directly to the UniFi access point on the UAV, in order to exclude the effect of the AirMax communication and router. This is marked as Test 4 in Table II.
- The PC with AUV command and control was connected via WiFi directly to the AUV using the original AUV wireless router, in order to also exclude the effect of the UniFi access point and the separate router. This is marked as Test 5 in Table II.

C. Download data rates

During tests, file of a total of 49 Mbytes were downloaded from the AUV to the ground station. Test results are shown in Table II. The difference in data rates between Tests 1 and 2 are primarily due to the motion, roll and pitch of the UAV. The difference in data rates between Tests 2 and 3 are primarily due to distance between AUV and UniFi access point, as well as distance between UAV and ground station. The difference in data rates between Tests 3 and 4 are due to the UniFi link between UAV and ground station. The difference in data rates between Tests 4 and 5 are primarily due to the use of a separate router and wireless access point.

It is observed that the reduction in data rates due to the UAV and additional links are quite modest, and could probably have been substantially reduced with router functionality onboard the UAV, e.g. in a WiFi access point. The bottleneck in the system appears to be the system onboard the AUV, which goes to 100 % CPU load during the download. With the communication setup, one might otherwise have expected performance closer to the theoretical limits of the 802.11b/g standards (i.e. 11 Mbit/sec or 54 Mbit/sec).

VI. CONCLUSIONS

Experiments were conducted under less than ideal conditions with rain and turbulent winds leading to unfavorable roll and pitch motions of the UAV. The results with data download from the AUV through the UAV communication relay to a ground station shows that at the tested (typical) flight conditions the distance and attitude between the AUV and UAV are not the bottlenecks in the communication network. The main bottleneck was identified as the capacity of the proprietary wireless system on the REMUS 100 AUV which seemed to be set up to provide a relatively low capacity wireless data link regardless of signal strength and quality. This link is very robust

Test	Setup	Avg. Data Rate
1	UAV loitering over AUV at sea	326 kbit/sec
2	UAV on ground with AUV at sea	353 kbit/sec
3	UAV and AUV in lab, short distance	426 kbit/sec
4	UAV and AUV in lab, ground station on 2.4 GHz wireless	518 kbit/sec
5	AUV in lab connected to 2.4 GHz wireless router	790 kbit/sec

TABLE II
TEST RESULTS WITH DIFFERENT NETWORK CONFIGURATIONS.

as no loss of connectivity was observed during the field test downloads. The tests also revealed the importance of the network configuration and a good link between the UAV and ground station in order to not waste communication capacity due to unnecessary network traffic. The UAV-to-ground station datalink is not given much attention in paper, as the design should consider local geography and there is considerable flexibility in its design using e.g. stabilized/tracking directional antennas, phased-array antennas with electronic beam-forming [16], and ground-based relay stations.

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