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Remote water sampling using flying robots

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***Abstract*— Sampling of water for laboratory measurements is important in various circumstances. We present reasoning why it is of great importance for sensible ecosystems like natural parks wich include wetlands. Since many places are hard or impossible to reach by other means, a system for sampling of water using an unmanned helicopter is proposed. The technical difficulties in handling the sample and controlling the system are described as well as apropriate solutions. The system was also integrated into a control framework allowing easy access and control by scientists, in our case biologists. Several trials have been performed, including flights in the final application fields. Water samples could be acquired reliably.**

I. INTRODUCTION

The use of unmanned aerial vehicles (UAVs) for environmental monitoring and research is growing in recent years [1], [2], [3], [4]. In the past UAVs where used for remote sensing applications, avoiding interaction or contact with the environment. But many applications exist that require interaction with the surrounding like taking a soil or water sample and bringing these samples back into a laboratory for analysis. Since UAV technology is improving rapidly, it allows to use this technology in many new scenarios. With these tools in hand we were able to design a system that can take water samples from the air in remote locations automatically as shown in Fig. 1.

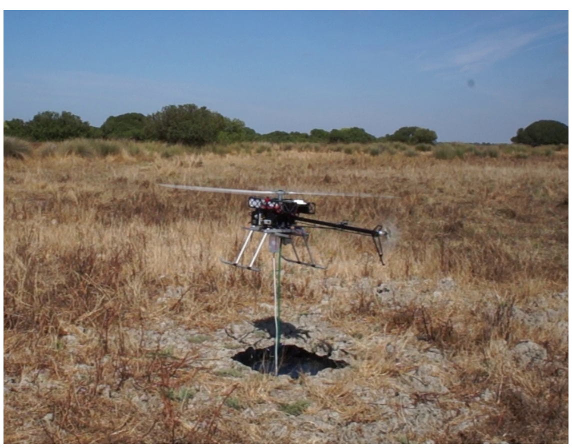

Fig. 1. Automatic water sampling demonstration in national park

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A. The importance of water sampling

Wetland ecosystems are part of our natural wealth and they make a vital contribution to human health and well-being [5].

Water pollution by nitrates, mainly from intensive farming practices has been identified as one of the most important threats for water ecosystems and it is causing problems in all European states [6].

The major environmental problems due to inorganic nitrogen pollution in aquatic ecosystems are water acidification, eutrophication and toxicity, which can affect the aquatic fauna [7].

Inorganic nitrogen pollution in aquatic ecosystems may produce even worse ecological and toxicological effects, especially under expected changes in global climatic conditions [8].

B. The need for water sampling

Biologist and management authorities need physicochemical and biological monitoring for assessing the risks due to freshwater pollution and to provide maximal information for adequate management of aquatic ecosystems [9], [10].

Doñana National Park (DNP), located in the right bank of the Guadalquivir river estuary in the atlantic coast (Andalusia, Southwest of Spain), covers 543km^2 and hosts a unique biodiversity. It was declared a Reserve of the Biosphere by UNESCO due to its great variety of ecosystems (marshlands, lagoons, scrub woodland, forest and dunes) [11] and its strategic location, which constitutes a major stopover for migratory birds from and to Africa [12].

Doñana is one of the most important wetlands in Europe and is included in the *Ramsar* list of wetlands of international importance [13].

C. Pollution scenarios in Doñana

Several authors have indicated that different water pollutants are threatening the Doñana ecosystem for the last 20 years. Although most of the studies have been focused in the negative effects of agricultural practices (mostly rice and strawberries) [14], [15], some also stated that urban pollution [16], and even pharmaceutical compounds [17] are affecting the quality of the water, with a high risk for the park ecosystem preservation.

Ramsar Conference of the Contracting Parties recommended to the Spanish government and regional authorities of Doñana to ensure better and stricter control of the use of chemical products for agricultural purposes [18]. Apart form those permanent risks, in 1998 Doñana was severely impacted by the release of 5 million cubic meters of acid waste from the processing of pyrite ore [19].

Aerial water sampling has the potential to vastly increase the speed and range at which scientists obtain water samples while reducing cost and effort, and unmanned aerial vehicles (UAV) have been used for this task [20].

In the context of the EU Project PLANET [21], in which all of the authors cooperate, field experiments are performed in DNP. The park includes zones that are flooded in winter and spring and dry in the summer season (Fig. 2). In case of an upstream pollution event in the flooded season, wide contamination of the sensible environment could occur again. The scenario described in the PLANET project uses different methods of remote sensing and sampling to evaluate the best response. Taking water samples by a UAV is an important part of this process since these samples could otherwise only be gathered by people in boats or on horses, which is tedious, could be dangerous and thus undesirable in a pollution event.

Fig. 2. Marshland in DNP

II. UAV SYSTEM

Technically, the process of providing samples of water by an unmanned flying system involves several challenging aspects. Since a quite close interaction with the environment is needed, control of the flying platform has to be performed very accurately and within tight tolerances. Furthermore, the addition of weight to the system in the process of sampling has to be compensated. Therefore, sensors used for control have to be very accurate. This applies to both the absolute position for control towards sampling as the relative position over the water in the process.

Since water is handled close to sensible electronic components, protection is needed. The water flow has to be designed accordingly. Additional protection of systems might be necessary. While most operations will take place at distances where the aircraft is visible (most of the times due to current regulations), the behavior of the sampling mechanism will most likely not be observable. As a consequence, as much of the sampling process as possible should be automated.

A. Helicopter system

The water sampling mechanism is attached to a helicopter UAV. The small scale helicopter has a rotor diameter of about $1.8m$ and a take-off mass including our modular autopilot system [22] of about $11kg$. The modular autopilot system allows to adapt the UAV system to new payloads very quickly. A differential GPS system measures the global position of the UAV. An inertial measurement unit (IMU) is used to estimate the orientation of the UAV at a rate of 100Hz.

This helicopter can carry about $2kg$ of additional payload. The precision position controller [23] can also perform automatic take-off and landings. Using this controller the helicopter can hover with a position accuracy of about $10cm$. This enables several applications for in situ measurements like presented in [24] and in this paper and to perform these tasks automaticaly without the need of an expert pilot.

The system has prooven robust against external influences like wind gusts and load changes. The accuracy of the position in hovering flight is better than 10cm in all directions. Flying time was tested to be up to 20 minutes.

B. Sampling mechanism

We evaluated several options for a sampling mechanism. The obvious first concept is to have a container suspended in a distance under the helicopter. The container is lowered into the water to be filled. An alternate solution for direct filling is the use of a winch to lower the container from a position close to the helicopter into the water for sampling. By using a pump lowered into the water, the container can stay fixed to the helicopter.

The requirements for choosing a sampling method are mainly safety and usability. See table I for a comparison of different aspects.

Mehtod	Entanglement	CG shift	Complexity	Handling
Suspended	high	high	low	medium
Winch	medium	high	high	medium
Pump	low	low	high	low

TABLE I
COMPARISON OF SAMPLING METHODS

Following the evaluation, a pump-based system was choosen mainly because CG shifts by a 500ml sampling container hanging underneath the helicopter were considered unsafe.

By using standard mounting rails a quick installation and interchange with other payloads is possible (Fig. 5). A pump was selected to provide short sampling times (10-15s) while being lightweight. Power and sampling hose include connectors that will release when a given force is exceeded. This would be the case if the pump or cable would get

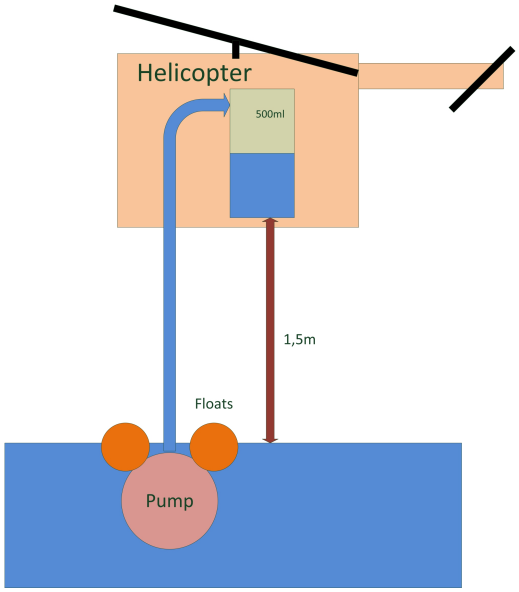

Fig. 3. Basic principle of sampling

stuck or entangled on the ground. The pump is activated by the autopilot system. A current sensor provides feedback of the pumping status. In this way it can be observed if the pump has a malfunction, is running dry or is pumping water (Fig. 4). This is very useful for automatic sampling, as the next paragraph will show. A system for sensing contact with the water can be saved by this method, saving weight and reducing complexity.

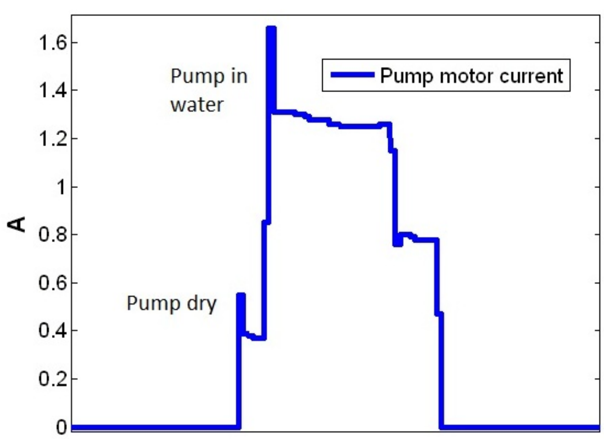

Fig. 4. Measured current of pump motor

As described in section II-A, the autopilot system is programmed using Matlab/Simulink. Consequently the sampling procedure is implemented using Stateflow. Easy programming and online debugging allow quick development and checking for problems.

The helicopter is commanded to the sampling position using standard guidance algorithms. When reaching the position, the water sampling method is activated. The altitude is lowered to a low level above ground and the pump is

Fig. 5. UAV with water sampling mechanism in flight

activated. If the current reading shows a free running pump, the helicopter is lowered until the pump intakes water which is sensed by increased pump motor current. The altitude setpoint is then commanded to a slightly lower value to ensure a fully submerged pump. A timer is activated. After the timer has expired, the pump is deactivated and the helicopter climbs to a safe altitude. Standard waypoint flight will then continue to deliver the sample.

All parameters (altitudes and threshholds) are adjustable to the sampling conditions.

Most sampling locations provide well known water levels and areas, allowing for pre-programmed flights using GPS as a reference and the pump as a final approach sensor. For areas with high variance in water levels or when only spots between dry land are to be sampled, additional sensors are necessary. If manual intervention is desired, a downlink of videos or pictures showing the targeted sampling location can be implemented. For an automatic system, a combination of a sensor measuring altitude over ground like laser or radar can be used. To check if water is present at this position, the currant measurement of the pump provides the necessary information.

C. Integration in control framework

All systems are connected to the PLANET framework, which gathers data and sends control commands via a central system including a special user interface for the end users (Fig. 6).

The desired positions for taking water samples are determined by algorithms and user interaction. Transfer to the UAV system is performed via a network using standardized messages. This procedure could be successfully demonstrated in the national park environment.

III. Flight Experiments

First experiments were performed with a transparent bucket of water at ground level. It allows close observation of the process, even how it works under water.

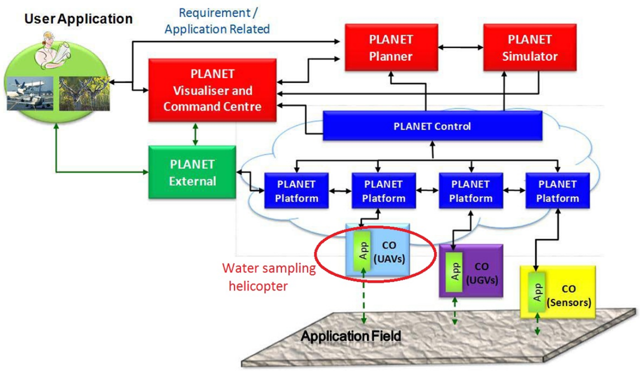

Fig. 6. PLANET framework overview

Further testing was performed in the environment of DNP which is the real world application scenario. Since the first set of experiments had to be performed in the dry season, an artificial water reservoir was built. The diameter was less then 2m. This demanded the position for water sampling to be very accurate. In a real scenario with large flooded areas this would not be the case. The system could take several samples and deploy the pump very accurately every time (Fig. 1).

Quick retrieval of sample containers and replacement by a new one was also demonstrated.

In a second set of experiments when DNP was partially flooded, the capability of the system could finally be demonstrated in spring of 2014 (Fig. 7). Several samples were automatically taken within the PLANET project experiments.

Fig. 7. Automatic water sampling application in national park

IV. Outlook

The UAV water sampling system is going to be improved and tested in the future. Automation of the sampling process is going to be improved. A sensing of sampling success will be implemented by using existing data. Sensors for altitude measurement are in test on other platforms at the moment, generating promising results for the presented application. Especially newly developed laser altimeters combine characteristics like being lightweight, providing high sample rate and reasonable prices.

Comparison of data gathered by traditional sampling methods and aerial water sampling is also planned. Recent publications [20] indicate the results should be expected positive.

V. Conclusion

Aerial sampling may be especially interesting in areas with dangerous access, or dangerous pollution. There are so many wetlands in the world threatened by pollution [25] that this method opens new business and research possibilities.

While the focus in this paper was on water sampling in sensible ecosystems, other scenarios like natural or human induced desasters could benefit from these capabilities.

VI. Acknowledgement

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Fieldwork was conducted in Doñana Biological Reserve, Southwestern Spain, a preserved area within Huelva and Seville provinces. Surveys took place in September 2013.

Doñana National Park authorities (Junta de Andalucía) approved permits to conduct this study.

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