Ground Support for Drone-based Industrial Inspections*

Ulrico Celentano[1], Marko Kauppinen[2], and Juha Röning[3]

***Abstract*— Unmanned aerial vehicles (UAV) can help in improving safety and decreasing costs in the inspection of industrial plants such as oil and gas pipings. UAV-based inspection brings endurance requirements and safety constraints to the inspection system as a whole. This article focuses on the ground support segment of the HYFLIERS inspection systems and more particularly it looks at effectively and efficiently supporting the inspection data flow and at competent and safe power supply.**

I. INTRODUCTION

In oil and gas facilities, pipes and vessels suffer degradation by their exposure to product, environment and mechanical demand. In order to avoid leaks or catastrophic failures of the components, it is of primary importance to investigate their condition. One of the most damaging effects is the loss of thickness due to corrosion, and non-destructive testing (NDT) through ultrasonic testing (UT) is commonly used. Oil plants include a large number of pipes arranged in complex pipings. Routine thickness measurements and visual inspection, when done by humans using man-lifts, cranes, scaffolding and rope access, is dangerous and costly. Aiming at improving safety and reducing inspection costs, HYFLIERS project [1] is developing a drone-based system, Figure 1, including a hybrid robot (HR) capable of flying and rolling on pipes, supported by a ground mobile support platform (MSP), subject of this article.

The MSP follows roughly the location of the HR and its role is to aid the flying and inspection operations of the HR (navigation support including obstacle avoidance to enhance safety, and optimised mission planning); to act as a hub for inspection data management (both ways between the inspection plant centre and the hybrid inspection robot, also minimising the transmit power constraints and hence HR endurance); and to aid in battery energy management, compatibly with ATEX (explosive atmospheres) zone op¡ The following Section II presents the related work, Section III presents the MSP in general, while Sections IV and V detail on inspection data management and visualisation, and on power supply management, respectively. Finally, Section VII summarises the article and highlights the further steps.

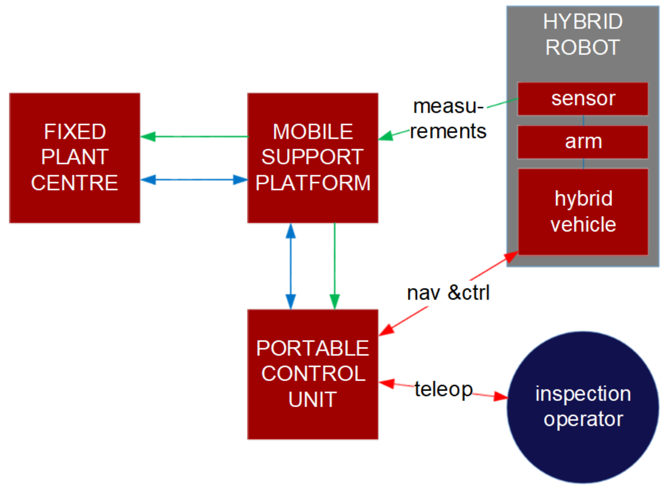

Fig. 1. The HYFLIERS system with its mobile support platform enabling inspection data flow between the hybrid robot and the end-user's site, and aiding the inspection operator.

II. RELATED WORK

The exploitation of unmanned aerial vehicles (UAV) and climbing robots has been identified as a solution to improve cost-efficiency and safety in pipe inspection. Wall-climbing robots are inspired by capabilities found in animals such as reptiles and insects but they require special materials and complex mechanical designs and dynamics analysis and they are typically cable-operated [2], thus limiting their reach. UAV-based inspection allows inspecting larger areas in a cost-effective manner [2], although for oil and gas facilities operating conditions may be challenging, especially in offshore environment [3].

As a part of a drone-based inspection system including a database of inspection images, [4] include a two-way data flow and human operator annotation for online labelling of inspection results. The authors of [5] depict a decision support system including estimations of maintenance need and suggested inspection rates based on thickness degradation monitoring.

Energy consumption in UAVs is critical, since propulsion is its main electric power consuming part [6]. Therefore, in addition to energy consumption optimisation, provision of a fully charged battery is needed to prolong the operating time. To achieve this, battery swapping or recharge through electrical contact or contactless can be automated or human-operated [6]. Whereas charging stations are suggested to be

*The research leading to these results was supported by the European Community's Horizon 2020 Programme, call H2020-ICT-2017-1, under Grant Agreement number 779411 (HYFLIERS: HYbrid FLying-rollIng with-snakE-aRm robot for contact inSpection).

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static, semi-static or even mobile (large UAVs equipped with large batteries) [7], wireless recharging includes the use of power lasers whose beam conveys energy to a flying UAV, hovering at height in a safe location [6] or more simply by resonant coupling using planar circular coils [8], [9]. In such a kind of wireless power transfer (WPT), coils alignment is crucial for efficient energy transfer. Alignment is ensured in [8] by the use of a drone-specific landing guide, whereas in [9] a two-axis motorised device is used to position a mobile coil.

III. Mobile Ground Support Platform

A robotic inspection systems needs to be operated by personnel with dedicated expertise. For UAV-based systems, a certified pilot is required for flying operations whereas a skilled inspection engineer is needed to guide or supervise the robot performing the inspection measurements and acquiring other information. To this end, proper supporting equipment is needed. A ground mobile platform may embed the required functions while also taking care of inspection data communication with the end-user's system and also aiding in power supply for the weight and energy constrained UAVs. This is the approach followed by HYFLIERS in designing the system's mobile ground support platform. The MSP power supply box supplies power for the MSP PC and the HR charging equipment.

The inspection system must be easily transportable by the inspection personnel and comply with workers' and operating safety regulations. The MSP is cased into a collapsible cart (based on Smartone Micro) whose wheels can be optionally equipped with brushless direct current (DC) motors to ease its movements. The cart hosts fixed at its bottom the MSP power supply box (including the main battery and alternate current, AC, power system). When open, see Figure 2, the top part of the cart makes room for hosting the detachable rugged water-resistant MSP computer (PC) case equipped with waterproof keyboard and mouse and an IP65 22-inch Beetronics 22TS7M Full-HD (high definition) multi-touch screen.

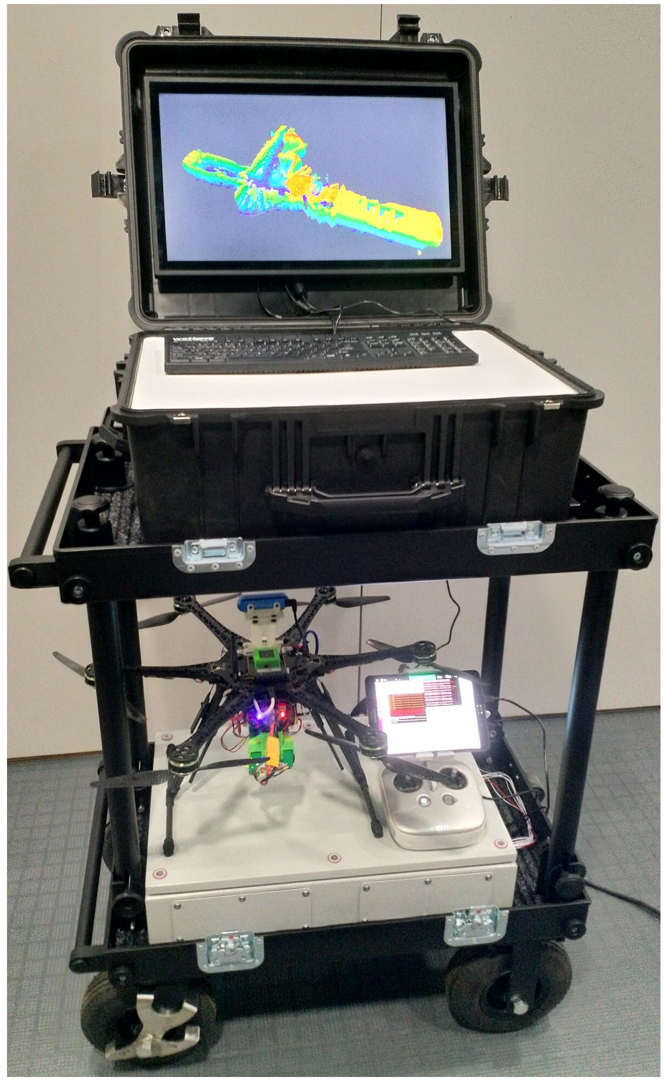

Fig. 2. The MSP cart open in operational conditions, showing the power supply box at the bottom and the PC case on top.

The MSP PC case also carries all the electronics for remote operation and support functions of the HR, including WiFi and Ethernet networking support as well as HDMI (high-definition multimedia interface) and USB (universal serial bus) ports for additional external devices. An external modem (4G/5G) is used to access external services on the Internet and other services provided by the industrial plant centre via the MSP. The MSP PC case is only connected to the cart and its DC-DC converter through a rugged two-pin power plug and includes a Zotac ZBOX computer for HR control and monitoring, and Asus ROG Rapture GT-AC5300 with WiFi antennas mounted inside the ABS plastic box. Database and navigation support functions may be provided by a separated PC.

Information flow is split for the inspection operator and the pilot operating the HR, see Figure 3. The pilot needs in their user interface (UI) only video feeds and controls they need to operate the HR. The MSP enables the inspection operator to inform the HR pilot about the inspection locations, e.g. during the approach or positioning of the UT sensor. During flight, the pilot's view is transmitted via the low-latency link through HR's remote controller and it runs over a DJI Lightbridge 2, which has minimum delay. Having a sophisticated UI for the pilot rendered on the HR's onboard computer is unfeasible when the autonomous operation of the HR requires a significant amount of onboard processing power, so only the video feeds from the HR are transmitted for the pilot during flight. The pilot's view can be forwarded from their controller to the ground station (GS) and the inspection operator, who has then access to control some parts of the HR's systems via an UI and can convey guidance information to help the pilot, without affecting the pilot's control over the HR.

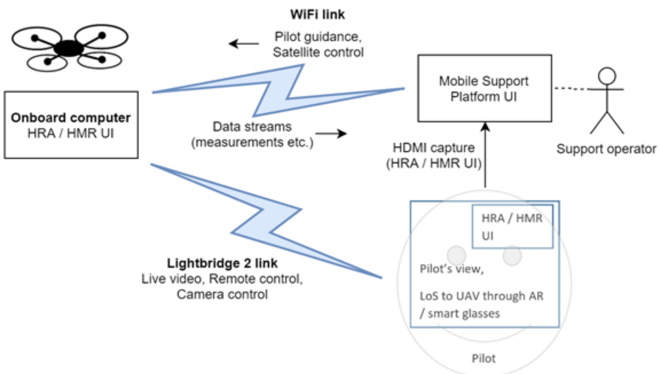

Fig. 3. Links among HR (either a HRA or HMR), MSP, pilot and inspection operator.

IV. INSPECTION DATA MANAGEMENT AND VISUALISATION

The MSP provides radio communication capabilities between the HR and the end-user's site by splitting the link into two hops, thus reducing requirements on transmit power, energy consumption and battery size and weight at the HR.

Figure 4 shows the interfaces between the MSP and the rest of the inspection system. With a DJI control system, multiple bands are used simultaneously: the 2.4 GHz band for control signal and the higher-frequency 5 GHz and 5.8 GHz for video. The 5.8 GHz analogue video receiver (Analog Video RX) link provides the lowest latency video from the HR, in case it is needed during the operations of the HR. The pilot's HDMI video output can be real-time read through capturing using by a Magewell HDMI to USB3 2nd generation UVC UVC (USB Video Class) capturing device.

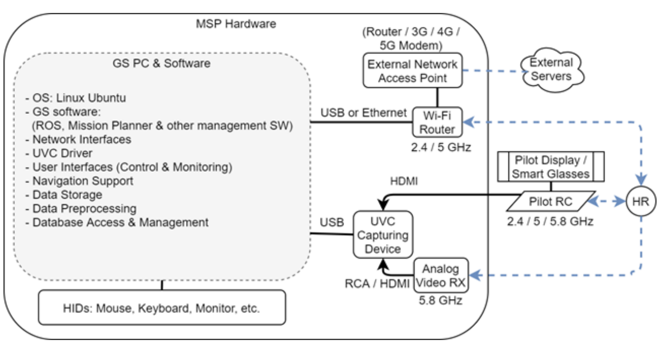

Fig. 4. Overview of the hardware and software interfaces among the MSP ground station, the HR and the external network.

Robot operating system (ROS) is used to interface with ROS-related traffic corresponding network interface connected to the HR, via the Wi-Fi router. The benefit of using ROS for data handling is to have one unified system for handling both the robot-related support functions and the data recording.

A. Inspection Data Management

Inspection data flow between the end-user's remote site and the hybrid robot along the chain of the HYFLIERS system through the GS.

Raw inspection data storage is handled by storing them in the local hard drive of the MSP PC; when ROS is used, this is done by using ROS bag data containers. Data preprocessing is required for parsing the recorded data to the format required by the inspection reporting system at the end-user side.

B. Inspection Data Visualisation

The MSP PC runs Linux Ubuntu 16.04 and the Nvidia Jetson TX2 onboard the HR runs L4T (Linux 4 Tegra) Ubuntu 16.04. Nvidia Jetson TX2 is capable of running YOLOv3 deep learning object detection system [13]. The MSP supports visualisation of HR sensor data, such as occupancy mapping using Intel RealSense T265 for odometry and D435 for depth measurements, see Figure 5. Real-time view from the HR is transmitted over the DJI Lightbridge 2 video link.

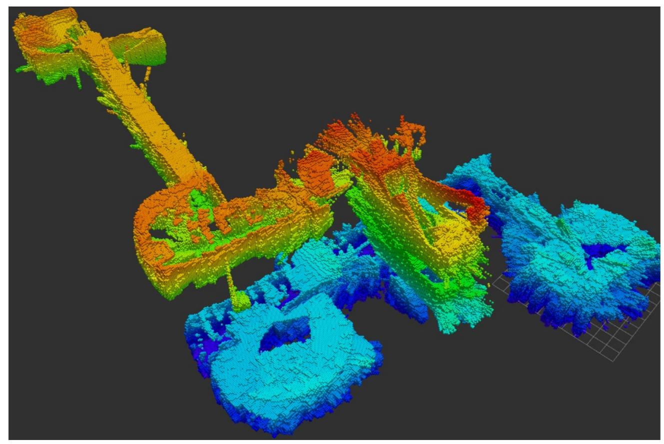

Fig. 5. 3D mapping with OctoMap using Intel Realsense cameras.

The MSP computer as a ROS slave system can subscribe to the ROS data streams produced on the HR. The ROS slave system can also connect to the flight control unit (FCU), and other nodes running on the HR, for commanding and receiving real-time data.

V. POWER SUPPLY AND DRONE RECHARGING

As seen in Section III, in addition to inspection data management, the MSP provides power supply to both the MSP PC and possible HR battery recharge.

A. Power Supply

The MSP power supply weatherproof box, includes the main battery pack, the custom power and charging power management system (PMS) module, the battery management system (BMS) module for the battery, and an AC-DC power supply unit. The simplified functional overview of the custom PMS board and main power box related electronics is shown in Figure 6.

The main power system of the cart is an eight-cell $LiFePO_4$ (lithium iron phosphate) battery pack, significantly safer and more reliable than other commonly available LiPo

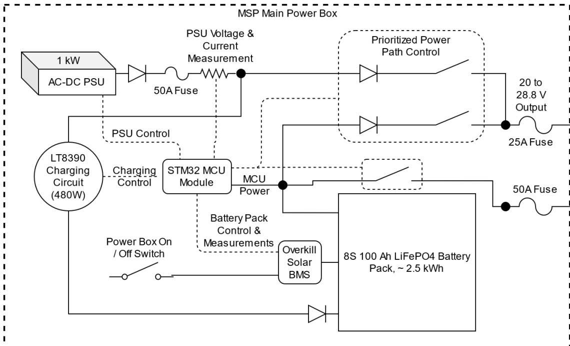

Fig. 6. Simplified scheme of the MSP power supply box.

(Lithium Polymer) battery chemistry, and offers a 105 Ah capacity.

The custom PMS ensures uninterrupted power supply, so that the MSP is able to work uninterrupted when it is connected and disconnected from AC power during operation and this is handled with a custom solution. The PMS board includes an LT8390-based charger, which charges $LiFePO_4$ battery at maximum 480 W power. The HR charger takes the power directly from the MSP main battery, which can output a large power for the charger without having to worry about supply capabilities to other support hardware.

During operation, the power taken by the GS PC and the HR charger is monitored, so the maximum allowed main battery charging power is determined. An STM32F446RET6 microcontroller unit (MCU) on the PMS board controls the power output and the real time monitoring and charging control of the MSP main battery. More specifically, the MCU handles the control of the LT8390EFE based battery charging circuitry, communication with the BMS, controlling the output of the AC-DC PSU and the real-time control of the power bus matrix between all the connected components within the power supply box. Other controllers in the power bus system structure are the LTC4421 power path controller for driving power path control N-MOSFET switches, and LM74700-Q1 for driving the N-MOSFET based low-loss diodes. The board has a connector for the external OLED screen, for showing the power box UI elements and measurements that are relevant to observe the correct functioning and status of the power supply box. Additionally, there are high-side current and voltage sensing integrated circuits (ICs) used in the bus matrix, like the INA240A3D current sense amplifier. The HR Battery Charger component shown on the right-hand side of Figure 6 comprises all the charging cases, either a battery charging dock or a contactless charger, see Section V-B. The battery charger output is cut off automatically by the MCU, when the available energy level of the MSP drops too low.

The power supply system is completed by the BMS module (Overkill Solar BMS 100a 8s) and the 1 kW AC-DC power supply unit (TDK Lambda SWS1000L-24 PSU), with mains AC input range of $85 \div 265$ V. The MSP power supply has an energy capacity of 2.5 kWh, with a voltage range of 20 to 28.8 V, which is subsequently the voltage output range of the MSP power box to the PC box and the HR charger. The power limit for the PC, including the user interface (UI) and communications related hardware, is set at 500 W. The HR charger DC power supply is limited by a fuse to 1000 W.

With the 2.5 kWh main battery, the system should be able to be used to charge the HR several times, in situations where an AC power is not available, while simultaneously running the GS PC and communications hardware.

B. Optional Contactless Charging

Swapping HR batteries may cause hazards in ATEX areas, and therefore it is forbidden so batteries can be swapped only in safe areas, which may be far away from the current operating location. A contactless charging system could offer a suitable charging option.

The system, Figure 7, consists of two helical coils in a coaxial configuration. The primary side coil fixed to the charging platform, and the secondary on the drone. Coils can be cased to form a sort of a plug to ensure mating but without any electrical contact thus avoiding risks of sparks.

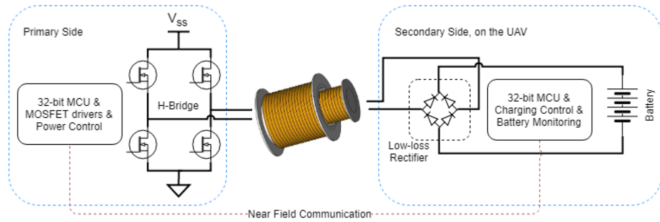

Fig. 7. Contactless charging system design.

The AC induced on the secondary coil needs to be rectified and regulated to the battery voltage by low-loss rectifier circuit. A challenge is that the frequency used may have to be quite high to have enough power transfer capacity without having coils that are too big and heavy, which makes the electrical requirements for controlling the system quite complicated. Also, the high-power transfer requirement may force to use a ferrite core on the primary side of the charging circuit, residing on the MSP, to keep the HR side connector as small as possible.

For controlling the charging system, the secondary side would utilise a the battery monitoring circuit and a microcontroller unit (MCU) to monitor the cell voltages and amount of power going into the battery. The cell voltages need to be balanced as well. For precisely regulating the current flow and the charging process, a wireless communication link needs to be established between the primary and secondary sides. For communications, near field communication (NFC) could be utilised to transmit data between the HR and MSP sides of the charger.

Wurth Elektronik [14] wireless high-power transfer circuit development kit 760308EMP is selected as a starting point for testing the implementation of the wireless charging system. The development kit comes configured for 200 W power transfer. The main components of our design, would be the Infineon IR1161L synchronous rectification controller, which can handle high frequency rectification (up to 500 kHz) on the secondary side of the charging system. With this controller, the power transfer capacity should be possible to be scaled up to above 1 kW range. The primary-side coil modulation is performed by an MCU controlling the current flow direction in the coil using four high speed MOSFETs in a H-bridge configuration. The communication between the primary and secondary side MCUs could be handled by an appropriate small NFC link.

A comparable power transfer system has been studied by [15], where they established that a roughly four-by-four centimeter helical coil could be used to implement power transfer of up to 1 kW with over 90% efficiency. They did not use a ferrite core in their system so relaxing the maximum power output to around $300 \div 500$ W and utilizing a ferrite core, it should be possible to significantly reduce the size of the secondary side connector that would be on the HR. However, using a ferrite core might not be feasible for very high frequency applications due to energy losses inherent to changing the magnetic polarization of the core material. If applied to contactless charging of the HR batteries, the fast-charge time would be the HR battery capacity, in Wh, divided by the maximum power output of the charging circuit. For example, if the HR battery capacity was 150 Wh, the charging would take roughly 30 to 45 minutes with a 300 W version of the charger. In practice, the HR battery capacity may be 400 Wh or more. The weight for the HR side circuit is targeted to be kept well under 100 grams.

VI. TESTS

The cart can be easily assembled and disassembled by a single operator. The mounted cart, 90 kg, can also be pushed by the operator, even without motorised wheels (Section III).

Access to oil and gas refineries for testing has been impossible due to travel restrictions caused by the pandemic infection from coronavirus disease (COVID-19). The correct functioning of the MSP hardware (MSP PC with the necessary network switch, router and regulators) has been tested in varying outdoor conditions in Oulu and at Ouluzone+ [17], including the communication and data streams over WiFi, and the point clouds produced by 3D sensors. The video link has been used to visualise the onboard Nvidia Jetson TX2 computer's UI while performing tests with ORB-SLAM2 [16] used for real-time SLAM (simultaneous localization and mapping) on the HR. The DJI GL858A remote controller, which is used for the Lightbridge 2 video link, was also used for piloting during the tests.

VII. CONCLUSIONS

Focusing on the ground support for a UAV-based inspection system, this article presented the realisation of a mobile platform to aid UAV inspection operations, including an inspection data management subsystem and the required power supply, with an option for wireless UAV recharge. The inspection data management subsystem is effectively serving the end user's needs while efficiently allowing communication between the hybrid robot and the site considering the capacity and payload limitations of the drone. The power supply system realises competent supply of energy to the mobile platform itself and, through it, for UAV energy provision, targeting also an optional wireless system potentially usable in hazardous environments if required.

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