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Prospective Configurations Of Optical Systems For Smart Remote Visual Testing Conducted With The Unmanned Aerial Vehicles

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Abstract: Remote visual testing of infrastructure, power plants and other important constructions is regularly conducted. It is regularly a crucial way of collecting data about the surface conditions and overall functionality of the tested objects. It includes a large number of technical, environmental and economic parameters, because of what researchers and experts constantly try to optimise it. The use of unmanned aerial vehicles (popularly known as drones) is a novel, currently rather undeveloped approach to conducting the remote visual testing. In this paper we present and develop a concept of a smart configuration for remote visual testing. It is innovative in that it includes a manipulator mounted onto an unmanned aerial vehicle of rotocopter type. Presence of a manipulator makes possible considerably augmented scope of remote visual testing, in comparison with other approaches. Prerequisites for, as well as consequences of such an innovation are analysed and mutually compared.

Keywords: nondestructive testing, optical systems, smart remote visual testing, unmanned aerial vehicles

1. Introduction

Visual testing (VT) is one among the non-destructive testing (NDT) methods. Its application is prescribed for accessible surfaces of statically and dynamically loaded constructions during their production and their service life-time, in order to detect surface non homogeneities (e.g. surface cracks or corrosion), before the functionality of the tested object is significantly degraded. Conducting VT as a rule includes optical systems, ranging from simple optical devices to complex optical instruments. Various aspects of the VT are available in literature. In order to enable the operators to visually inspect all required parts in all the variety of their environments, a significant set of auxiliary constructions, such as scaffolding, girders, lifting equipment, manual or automatic manipulators; has been developed and utilized. Since constructions to be visually tested often include parts that are difficult or impossible to reach directly by a human operator, during times a remote visual testing (RVT) emerged as a subset of specific VT techniques. Its characteristic is that human operator is at a distant position from a tested part. The visual information about the tested surface in that case is sent to the operator using long enough optical system consisting generally of different optical instruments and/or devices, or cameras which are connected with wires or wirelessly. The RVT generally requires smaller preparation time and auxiliary constructions, yet provides the operator with a generally smaller amount of visual information about the tested part. Recent and rapid development of remotely controlled semi-autonomous or autonomous, ground, underwater or aerial vehicles has started to change the RVT. The overall benefit to RVT, which is expected after inclusion of such vehicles, is that preparation time is reduced, while simultaneously the needed auxiliary constructions are to become lesser in quantity. It is expected that a new elements of the testing procedures will become important, such as is fly path design. However, overall, the costs and duration of RVT enriched with the remotely controlled vehicles are expected to lessen without reduction of the RVT quality and reliability. To complete the context, one must be aware that because of a constant tendency to lower costs it has from some time ago been noticed that inspections (without UAVs) has become less frequent, less thorough but more dangerous [1] so one expects that additional innovation is needed solely to preserve or lessen the observed negative tendencies, which is another function that the use of UAV in RVT is expected to make possible. In this paper we contribute to the development of the innovative and comprehensive use of the unmanned aerial vehicles (UAV) in RVT. The UAVs, popularly referred to as drones, has been used in recent years in a considerable number of applications, thus also in RVT part of NDT [1]. The variety of their applications constantly enlarges. Despite that variety, UAVs are generally utilized instead of humans in tasks which are dangerous, exhausting or too simple for humans [1]. Large portion of the UAVs applications includes aerial collecting of visual data: camera recording for defense-related surveillance and mission coverages, agriculture and wildlife monitoring, crisis management, infrastructure testing and other kinds of civil engineering support, etc. Within the scope of this paper, in which the focus is on transforming the largest possible tested area into UAV-accessible region, we do not differentiate between the outdoor or indoor applications of the UAVs. Yet, there are significant differences in regard to automatic navigation and to exposure to environmental influences, e.g. wind. The UAVs utilized in RVT are as a rule rotocopters, because they can hover, change flight direction in a smaller area than UAVs with fixed wings (UAVs that are lighter than air are generally not suitable because of their too large dimensions and too large flight inertia) and they have the capability for vertical take-off and landing – VTOL. Majority of rotocopter UAVs have four rotors (usually denoted as quadrotors or quadcopters), six rotors (hexacopters) or eight rotors (octocopters), Fig. 1.

Figure 1: *Examples of rotocopter UAVs. From left to right: quadrotor (quadcopter), hexacopter and octocopter [2], [3]. Another type of rotocopter, the helicopter, is not shown.*

From the point of suitability for RVT, we differentiate between two configurations. Taking into consideration the maturity of their use and the demands onto underlying processing capability, for the purpose of this research we refer to these two configurations as to the conventional and the smart use of UAVs, Fig. 2. In a conventional use (Fig. 2a), which has been extensively developed in other fields, the UAVs functions as a camera mount. Corresponding use has been well developed in a large number of fields [4], and already prescribed in some areas, e.g. petrochemical industry [5], [6] or civil engineering [7]. Basically, the conventional use means that UAV flies around the tested surface, sufficiently far away from the tested surface and other obstacles, simply recording the surface conditions. Nevertheless, the accompanied image processing is by no means simple [7], [8]. Because the environment conditions (especially variable wind strengths and directions) change otherwise constant parameters (e,g, projection, illumination and brightness of the tested surface) a complex signal processing is needed that simultaneously takes into account data from diverse sensors [9]. In a conventional configuration the UAVs function as a remotely controlled aerial platform for high resolution CCD camera, that provides the operators and other interested personnel with the real-time high-quality visual data, in considerably lesser time with considerably lower costs than before [10]. While such an approach is suitable for determining the general condition of large surfaces, an example of which is the corrosion mapping, it is not suitable for detailed inspection, i.e. for making possible detection of small, yet important indications, an example of which is a surface crack. That deficiency has been known for some time ago, and attempts were conducted in order to overcome it. For example, in [11] authors develop and use a UAV based NDT which includes piezoelectric sensor capable of detecting vibrations of the tested structure, previously excited in some way. Authors of [11] expect that the use of UAV in such a way can augment the scope of the use of UAVs in NDT.

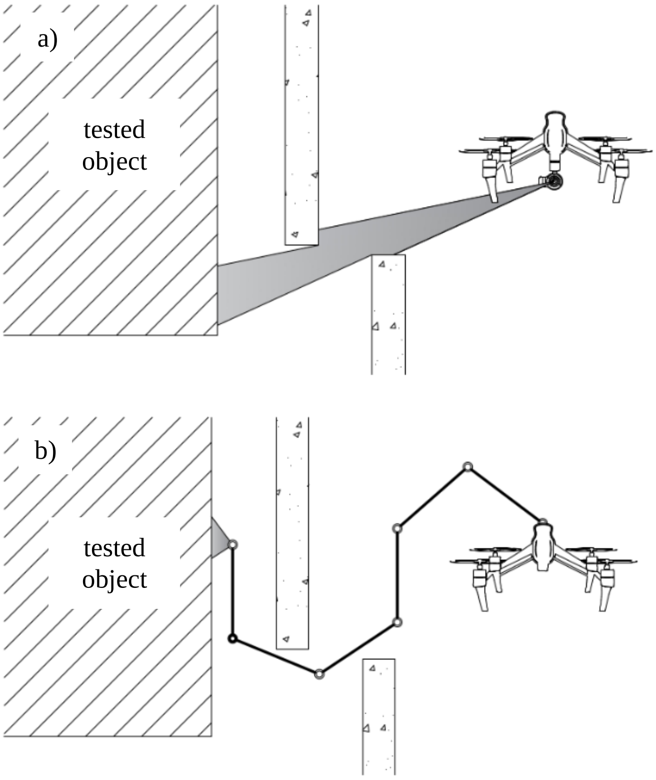

Figure 2: *Two configurations of a remote visual testing with UAVs: a) conventional, b) smart. Shaded area represents optical rays recorded by cameras. There is a significant difference between the areas of a tested object surface which are accessible to visual testing in these two configurations.*

Contrary to the conventional use, the smart use of UAVs, Fig. 2b, is important for inspecting the complex geometries. That configuration focuses onto finding the optimal parameters for conducting the testing so that the quality of the RVT is within the required limits, while the UAVs trajectory is optimized in duration and energy consumption. Since the region through which the UAVs fly is as a rule in the close vicinity to the tested surface, and generally has a significant portion of surface mounted elements or other obstacles both for the UAV path and for the surface testing, that is by no means trivial task. The processing power of the UAVs underlying processors, as well as the complexity of the exploited algorithms is to be significant and definitely considerably larger than in the conventional case, thus deserving to be denoted as a smart use of UAVs in RVT. Moreover, while in the conventional case the human operator can conduct the testing using the remote controlled UAV, in the complex tested geometry (such as the one sketched in Fig. 2b) it is assumed extremely difficult to simultaneously arrange the proper position of both the UAV and the manipulator with all its degrees of freedom. Before proceeding, two remarks are to be stated. First, it is to be noted that our research focuses on the UAVs, but does not exclude other types of vehicles. Indeed, our results can be utilized in RVT with underwater and ground vehicles, as well as in manual operations. Yet, the aerial use puts the stringent limits to the overall mass of the researched devices and their energy consumption. Because of that, the costs of the equipment make it often inappropriate for all types of vehicles but the UAVs. Second remark is that the use of UAV is not limited solely to conducting a RVT. Indeed, the

UAVs can overcome the problems in transporting sensors to the very position where an operator conducts direct VT or some other NDT method [12]. Table 1. summarizes different aspects of the use of UAVs in RVT, as discussed in details previously in this section. The paper develops the concept of smart use of UAVs in RVT. Among the large variety of possible realizations of such a use, we assume a generic RVT in which an UAV carries a camera and a manipulator that includes an optical system. The novelty of our approach is that the manipulator is of modular structure, mounted to the UAV on the tested site just prior to flight. Having all stated in mind, the problem is how to design the manipulator so that is makes possible traversing significant portion of the vicinity of the hovering UAV that carries it. The software control of the manipulator dynamics is out of the scope of this article. Our approach is, thus, a part of the overall approach to enrich the autonomous vehicles with manipulators, which has been more developed in regard to ground-based autonomous vehicles [13], [14]. Overall, the aim of that optically enriched manipulator is to enable the UAV camera to record the areas which are beyond its line of sight. The overall trajectory is complex because of the aforementioned aspects of the traversed region as well as because of the non-trivial, variable in time geometry of the UAVs with the manipulator mounted onto it.

***Table 1:** Comparison of the RVT which utilizes UAVs (left column) with RVT without UAVs (right column). Tick marks and cross marks denote that the corresponding RVT technique is for the aspect considered advantageous and disadvantageous, respectively. Circles denote that the corresponding RVT technique is neither advantageous nor disadvantageous for the related aspect.*

Testing aspect	RVT with UAVs	RVT without UAVs
Duration	✓	×
Auxiliary constructions	✓	×
Supplies	o	o
Total cost	✓	×
Personnel skills*	×	✓
Equipment lifetime	×	✓
Waste disposal**	×	✓
equipment storage	o	o
testing resolution and overall quality	o	o
environment influence***	×	✓
ambient temperature	✓	×

*the possible differences in VT experience and overall personnel reproducibility are not considered as they exist within each VT technique, here only the skill of flying a UAV is considered
**worn batteries
***for outdoor applications, rain, snow and haze prevent the conduction of each of the two RVT techniques equally. Here we consider the influence of the wind for outdoor applications. For indoor applications there are no differentiating environment influences

The paper is organized as follows. In section two we conceptually develop the UAV configuration suitable for smart RVT. In particular, we present generic forms of the utilized manipulators and the accompanied optical systems. Moreover, we list and discuss the criteria imposed onto the manipulators and onto the optical system components. In section three we classify possible classes of manipulators and the optical systems, and rank them in accordance with the stated criteria. In section four we conclude our research and provide the perspectives.

2. Concept of the UAV for smart RVT

A generic configuration of a UAV for smart RVT that we consider, includes an industrial multirotor UAV with a manipulator that has fixed members mutually connected with separable joints. At its end closer to the tested part there is a miniature objective. The other end contains a memory device. The optical system can have one of the following three configurations: (1) miniature camera in the objective, (2) fiberscope cable containing of optical fibers, or (3) system of lenses and other optical devices aligned so to transfer the picture of the area, as seen by the objective, to the (only) camera of the UAV. All these configurations represent additional mass of the UAV to be carried during the whole flight, no matter whether it is in use or not. Furthermore, inclusion of any configuration requires additional energy consumption: for the motors in joints, for the light at the objective end as well as the energy for additional processor work that determines the transfer of the additional data. Moreover, based on the existing configurations for RVT without aerial vehicles, one can expect that fiberscope adds the largest portion of mass. Inclusion of camera at the end near tested part is to be the most expensive having in mind the current prices of relatively small and robust cameras of sufficiently high resolutions. Thus we proceed with the configuration (3), as sketched in Figure 3. Having in mind that in visual inspection one conventionally utilizes fiberscope as flexible-rod endoscopes and borescopes as their rigid counterpart, the listed configuration (3) functions as a hybrid endoscope consisting of modular borescopes, i.e. overall flexible structure consisting of rigid members. The precise level of flexibility, expressed through the angle between the neighboring members, is expected to surpass the flexibility of a fiberscope for its segment of the same total length as is the length of two members in the configuration (3). For simplicity, further in the text we refer to that configuration as to the modular endoscope (ME). Position of the joint of the manipulator with the UAV influences differential thrust of propellers. Indeed, for the identical shape of manipulator, the set of thrusts on the propellers mutually differs among the variant A, B or C.

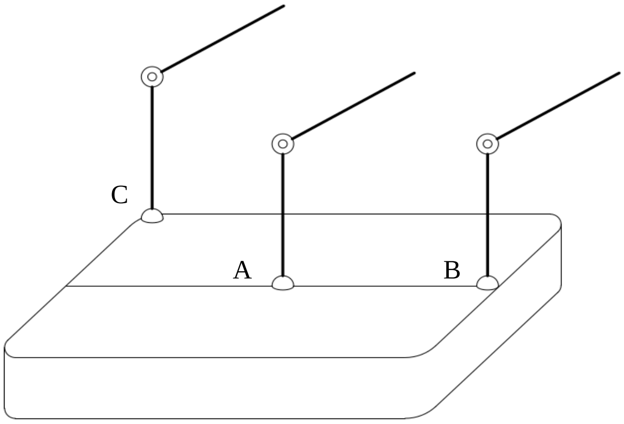

Figure 3: *Sketch of two different mounting of a manipulator onto a UAV for use in smart RVT: A - central mount, B - side mount and C - edge mount.*

3. Concept of the manipulator of a drone used in smart RVT

For practical purposes, modularity of the endoscope is best achieved by making the individual members mutually identical. Their number in a particular testing depends on the distance from the UAV to the tested surface during the testing, on the motors' thrusts and on the duration of a testing in regard to the battery capacity. It is expected that just prior to flight/testing an operator makes an assembly out of the needed number of members, thus forming the ME of a required range. In a commercially conducted smart RVT, for a given testing position such a parameter as is a number of joined members would be by no means prescribed and written in the standard operating procedure that covers the testing, along with the duration of testing with a single battery set. A single degree of freedom in the joint of neighboring members is shown in Figure 4. The angle of rotation of upper (in the Figure 4) member in regard to the lower member ranges, in principle, from 0 to 360°.

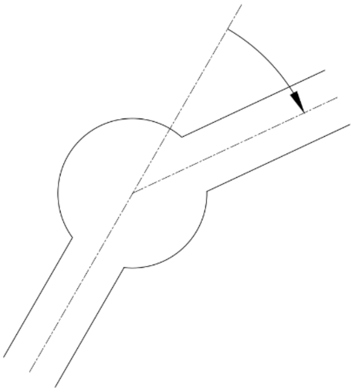

Figure 4: *Detail of the manipulator: joint between the neighboring members. Angle shown refers to the single degree of freedom of that joint.*

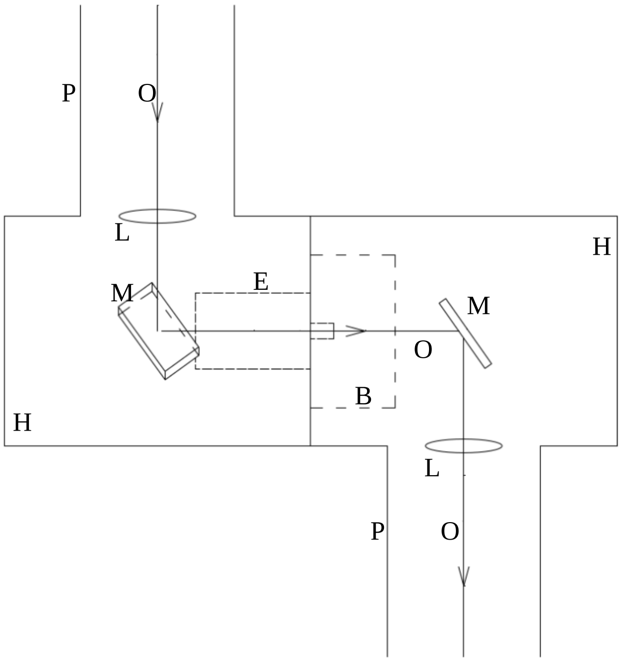

Figure 5: *Detail of a joint between the neighboring members of a manipulator. O – optical ray, M – mirror, L – lens, E – electric servo motor, B – bearing, P – pipe body of the member, H – head end of the member. Some elements are not shown in the drawing because of simplicity.*

There are three requirements imposed onto a member:

1. mechanically it should be sufficiently strong
2. electrically it can conduct sufficiently large electric currents
3. optically it makes possible transfers of high quality visual data in real time

Let us discuss these requirements in more detail. Mechanical requirement is imposed because a member must carry all the weight of further members and the objective. Along with the weight, because of the flexible joints, a member must have sufficient bending strength. Surely, in order to make the weight as small as possible, each member should be optimized so to have the smallest total mass. That mass is the sum of masses of the member case (in the pipe-like body and in the head), optical components (lenses and mirrors), electric servo motor and conductors as well as of the internal mechanic parts and mounts of previously listed elements. Having in mind contemporary material properties, it is expected that carbon fiber could be utilized for a rod as the largest part of the member, while some other polymer could be utilized for the case of the joints and internal mechanic parts. Since in one end of the member there is a motor, then through the interior of the each member the electric conductors, e.g. wires, pass. Partly they feed the motor at the end of that very member, and partly they make possible passing of electric current to further members. Along with that, one expects some insulators, connectors and possible impedance matching parts of a thereby formed electric circuit of a variable length and electrical characteristics such as is its total resistance. Before proceeding, it is to be noted that the manipulator, thus also any of its members, does not contain batteries as they are located on the platform, i.e. the UAV. Optically, in order to have relatively cheap instrument but of a sufficiently high quality and high resolution picture, the transfer of the visual data is realized using lenses and mirrors. Here we will discuss one among many possible combinations of optical components. The optical path through a member body is assumed coaxial with the symmetry axis of the body, i.e. the pipe. Within joints the optical path goes from one member to the other using a precisely positioned set of small mirrors. They are expected to be of a smaller mass than prisms or other optical elements performing the same transformation of optical beam. Lenses, as additional optical elements, have the function to make the diameter of the optical beam as small as possible. The stated requirements are to be optimized simultaneously as one interferes with the others. To illustrate that point note that the larger overall mass of an optical system influences mechanical characteristics of the members. Conversely, smaller total mass requires minimization of optical system eventually introducing the optical components that degrade information in optical rays they convey. Furthermore, faster positioning of the ME implies electric servo motors of larger power, thus also of larger mass.

4. Conclusion

Remote visual testing conducted by unmanned aerial vehicles onto which a suitable manipulator is innovatively mounted, offers the possibility of significantly broadened use of such a type of testing. Yet, because of the need to simultaneously govern the total energy consumption, flight stability and tested surface record quality, such an innovative approach is non-trivial and requires careful hardware and software optimization. In this paper we develop conceptually a prospective realization of such an approach, and present the possible corresponding initial configuration.

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