Unmanned Robot System for Structure Health Monitoring and Non-Destructive Building Inspection, Current Technologies Overview and Future Improvements

C.-H. KUO, A. LEBER, C.-M. KUO, C. BOLLER, C. ESCHMANN and J. KURZ

ABSTRACT

Inspection is a major issue with respect to the integrity and health of engineering structures. Many of those structures deteriorate at locations that are difficult to assess (for example a roof of a very tall building). State-of-the-art inspection methods are mostly visual inspections completed by trained inspectors, where inspections are time consuming, costly and dangerous. In order to reduce the risk and cost and increase the accuracy of inspection/monitoring, unmanned robotic systems (aerial or ground based) can therefore be of invaluable help. The research groups at both Fraunhofer IZFP and Saarland University have carried out experiments using micro aerial vehicles equipped with an off the shelf camera for building inspection and structural health monitoring over years. Many of the state-of-the-art technologies regarding image processing, robotics and 3D model reconstruction have been tested and evaluated with real engineering applications. The first part of this paper will be discussing our experience, the limitation of state-of-the-art technologies and experimental results of building inspection/monitoring, which includes methods of displaying image results in both 2D and 3D. Based on the results of the first part, the second part of the paper will focus on the improvement of image acquisition and stabilization. The last part of the paper will be discussing how other developments in robotics system (both aerial and ground) have a potential to fulfill future requirements in terms of building infrastructure life cycle management.

INTRODUCTION

An enhancing amount of civil infrastructure (i.e. buildings, roads, bridges etc.) has become an issue with regard to their ageing process and hence life cycle management. According the FHWA (Federal Highway Administration) nearly 70% of bridges and roads in the USA need to be inspected regularly [1~4] and inspections are purely

C.-H. Kuo[1)] , A. Leber[2)], C.-M. Kuo[1)], C. Boller[1) 2)], C. Eschmann[2)], J. Kurz[2)]: [1)] Saarland University, Mat. Sc. & Technol. Dep., Chair in NDT & QS; [2)] Fraunhofer Institute for Nondestructive Testing - IZFP, Saarbrücken / Germany

visual with inspectors present on site [6~8]. Apart from bridges any other type of infrastructure is currently not subject of clear regular inspection although this may become increasingly relevant with an infrastructure's advanced age. With many of the infrastructural buildings to be inspected inspections can become dangerous for the inspector as well as time consuming [9-12]. Most of those inspections (nearly 95%) refer to visual inspection. Automation of the process using a robot (or multiple robots) equipped with digital cameras may be an option interesting to be explored since it can be used to replace the human inspector. Using a robot for inspection has already become popular in North-America and Asia mainly concentrating on bridge or road monitoring. This paper focusses on this as well, using mainly aerial robots (UAV or MAV) for building inspection.

INSPECTION METHOD

The inspection method used is based on a MAV as an octocopter equipped with a digital camera underneath as shown in Fig. 1. The MAV is flown remotely and scans the building to be monitored. The camera is set to be continuously triggered with a frequency of 3Hz, which is also known as the time based method of image capturing. Even though the robot is fitted with a GPS receiver and has GPS guided capability, the entire flight process is manually controlled. This is due to the lack of signal when the vehicle flies close to a wall. The autopilot only provides auto-stabilization and altitude hold.

Fig. 1 Octocopter MAV system with digital camera

To successfully run the photographic monitoring initially, a flight route well planned is most essential for which the two most popular solutions are shown in Fig. 2. Since the camera image ratio is 4:3, a horizontal flight route will produce a series of pictures with lowest achievable distortion, which is the reason why a horizontal scanning is preferred.

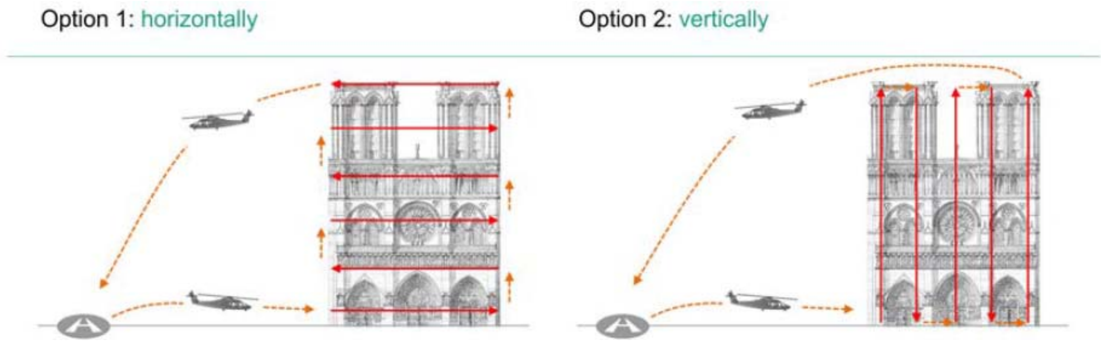

Fig. 2. Flight route for building inspection. [12]

To monitor a building a volume of several GB of data is recorded which is equivalent to thousands photos. After having all the pictures made, the major challenge exists in stitching all the images together. This challenge increases with the decrease of the damage size to be seen and hence the resolution of the photographs obtained.

There are two main image stitching software/algorithms being commercially available as well as even open source. The first one is called »aerial mapping« and second is »panoramic image mosaic« respectively. Aerial mapping uses geo-referencing data such as GPS coordinates of each photo to perform "image stitching". Unfortunately this method is difficult to be used for the case considered here since GPS signals are not accurate enough or even get lost when the UAV/MAV flight is close to a building which is the case when high resolution images are to be obtained. Secondly, aerial mapping is mainly configured for flight at high altitude where the ground buildings are assumed to be "flat". 3D features on the building such as window frames will therefore not appear as such and makes the algorithm unsuitable. The panoramic image mosaic algorithm has its limits with respect to applications for building inspection as it assumes the camera to be fixed at one point around which it can only pivot horizontally. However with an aerial robot this point can move in all directions in space which makes it therefore difficult to find the appropriate reference. As a result a significant number of the photographs taken has to be removed from the picture series and those have to be principally considered as noise. Different of the commercial stitching tools have been used however the results obtained are insufficient as can be seen from the example shown in Fig. 3. The only possibility to obtain an overall picture with acceptable resolution in accordance to the scales required is therefore currently still through manual image stitching which is a relatively laborious process but has been applied for the example described below.

TEST CASE

The approach described above has been applied to a major listed building which has been built more than fifty years ago. The building consists of 7 floors (around 30 meters high) and is around 100 meters wide. Each floor has a very similar visual image consisting of 70 windows each. A view onto the building is shown on Fig. 4.

Fig. 3. Results obtained with partial automatic stitching, Note that window size changes are due to movement of the helicopter during flight.

Due to lack of quality and maintenance as well as the cost incurred concrete portions can currently come off the building. The building is therefore inspected at regular intervals where cracks are recorded and mapped manually into a drawing while loosening concrete portions are removed at the same time. This work is so far only possible by moving an inspector with a fairly large lift along the building, which is an extremely cost and time consuming process that cannot be repeated too often. Access to the building has been rather limited as might be recognized from the aerial view on Fig. 4 (left).

Fig. 4 Building monitored, aerial view (left), front view (right)

A eight rotors micro-helicopter (octocopter) as shown in Fig. 1 was selected as the inspection robot. It offers sufficient payload capacity, is small in size, and most importantly it consists of a simple mechanical structure. The digital camera is a 12 megapixel Cannon SX230 with an image ratio of 4:3. Manual image stitching was selected for the whole process. The stitching process was split into different floors to fit to the monitoring approach. The overall stitched facade images were around 30 gigapixels. In addition some detailed photos were captured of damaged areas on the top floor which was inaccessible by the conventional inspection method. The building consists of many 2D facades which may cause confusion when all facades are displayed on one page. Thus a simple 3D interactive model was generated by combining the overall stitched images in a CAD software (Fig. 5).

The inspection time for the complete façade was 4hr (consisting of 1hr flight time and photo checking) without shutdown of the building. This is a significant improvement when compared to the conventional method which takes up to two working days consisting of an inspector with a basket lift who track moves along the facade of the building with visual inspection but no digital data recording. Fig. 6

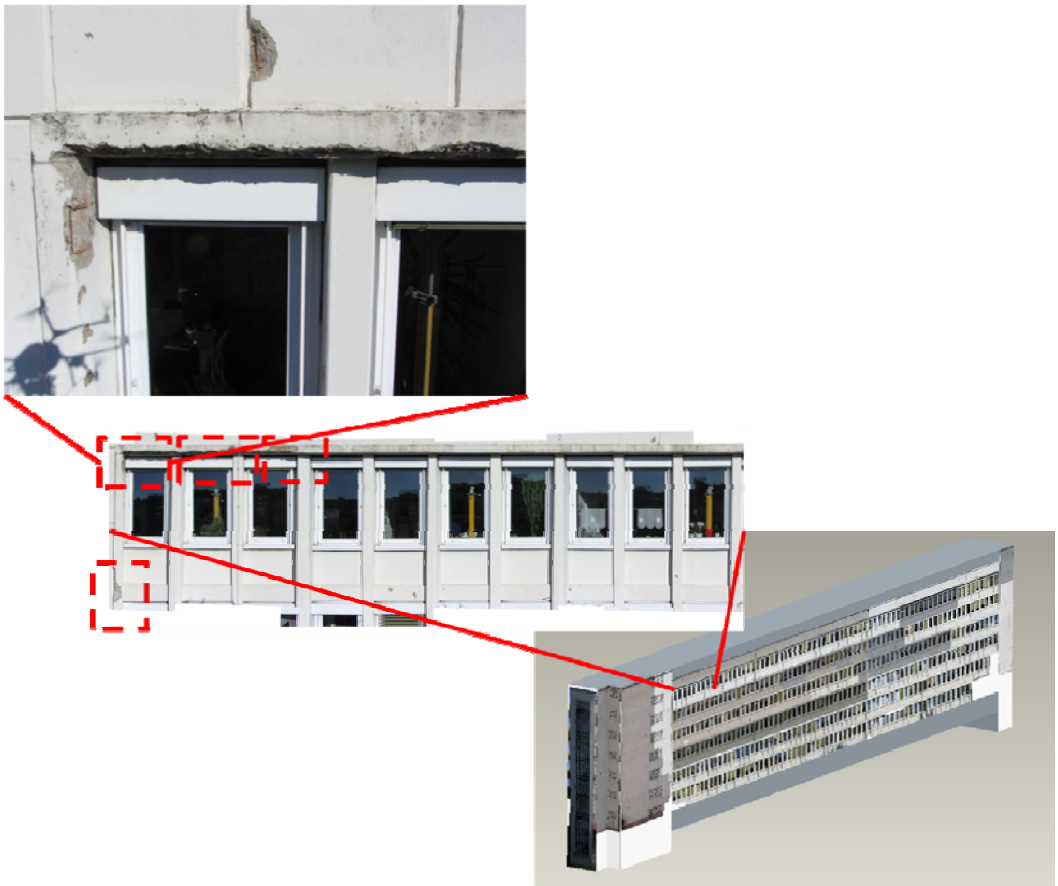

Fig. 5 Single image (top), manually stitched image (middle) and stitched sections added onto CAD model (bottom)

Fig. 6 Fully stitched image of the building to be monitored

shows the complete image of the façade of the building monitored. It is worth noting that there are light and dark patches on the image. Those result from the fact that the building was recorded twice and this at different weather and hence illumination conditions. This proves that the procedure has even the flavor that any updates regarding recordings can be included at virtually any time without having the building to be completely scanned again. Another observation that can be made is that not all of the building at the bottom can be seen. This results from the fact that the MAV has to fly at a certain distance above the ground which does not allow the adequate pictures to be taken from the bottom portion of the building. The same applies with regard to bushes and trees close by the building where the MAV is not able to fly because of space as well as possibly even aerodynamic reasons. Recording of the bottom sections of a building may however be achieved by using a ground vehicle travelling in front of the building with a camera system and with the help of a telescopic extension enabling even different photographic traces to be taken at high resolution allowing large sections of a building's bottom to be monitored.

NEXT STEPS TOWARDS LIFE CYCLE MANAGEMENT

The option to stich selected images even into a complete image of a building has the specific flavor that histograms can be established for selected areas prone to damage or where damage gradually progresses. An example of such a progressing damage is shown in Fig. 7, where the same location has been monitored within distance of 11 months. What has been seen as a slight crack pattern initially has turned out to break off some months later. Such a time series of pictures allows damage propagation to be observed in a first place. This is specifically important with concrete structures where processes of damage propagation are much less known and design configurations applied are various. With the approach proposed here a database of damage accumulation case studies can be provided that can serve for any kind of validation in excess of monitoring buildings in accordance to state of the art techniques. The approach is furthermore useful for facility management when facilities may be spread over hundreds of kilometers and more.

Fig. 7. Historical image for damaged area (11 months apart)

Assessing buildings in terms of their damage condition in the way described here however does not only require automated image stitching to enhance the monitoring process. What is further required is an automated pattern recognition procedure that allows damage patterns to be recognized and quantified such as it is shown on the left hand side picture on Fig. 7. Parameters may be derived that will allow damage conditions of reinforced concrete structures to be quantified which becomes a novelty for structures where damage tolerance has not been a parameter of their design initially. However the increasing number of ageing civil infrastructure made of reinforced concrete will require damage tolerance principles to be applied wherever possible if those should still be operated beyond their design life. The application of damage tolerance in civil engineering can therefore become an essential economic factor when considering investment and depreciation cost of this infrastructure in general.

Since damage accumulation is a nonlinear process the advantage of damage prognosis and hence damage tolerance increases the earlier and therefore smaller sized a damage can be detected. This is very much associated with the resolution a damage can be detected. Resolution again very much depends on a the camera system used, the means of signal processing and last but not least also on the flight stability of the MAV. Any translation in x, y and z direction of a multi-rotor robot will require attitude change due to the fact that the motions are all controlled by a difference in rotation speed of the motors. This attitude change is a source of noise during the image capturing process, even when the camera has a gimbal stabilization. However, translation in any x, y and z direction is required for the inspection. Therefore a vector thrust system is proposed and under development to remove attitude changes when a motion is applied to the multi-rotor robot [13].

A further means to enhance resolution of the damages to be monitored is to go beyond the visual imaging proposed here. Nondestructive testing allows a variety of further principles to be used which do allow even to look below the surface seen visually, at least to a certain degree. Techniques among those which have already been applied with success on concrete structures include radar, microwaves, thermography and ultrasound. With the exception of ultrasound, where a coupling medium is required all other techniques are coupling free which make them worth to be considered to be applied on a flying robotic vehicle. Data generated with those techniques can be merged with the data obtained from visual inspection which will gradually allow a view into the 3D volume of the building to be inspected.

CONCLUSIONS

The increasing number of ageing civil infrastructure requires means of at least semi-automated inspection which can be performed in moderate time and at acceptable cost. This is required to manage the operation of such an ageing civil infrastructure since structures deteriorate in a scattered manner over a longer period of time and hence their age does vary for a variety of reasons. This period of scatter in time can only be taken advantage of if damage accumulating is monitored such that the damage occurring and monitored can be tolerated. Otherwise the ageing infrastructure considered would have to be removed since its original design has been based on safe life design.

Monitoring of civil infrastructure is done generally by human beings. This is time consuming and costly and can therefore only be made at very few occasions.

However allowing damage tolerance principles to be applied requires monitoring to be performed at shorter intervals. The shorter the time intervals become the more benefits can be taken from the damage tolerance principle and hence from the civil infrastructure itself. Monitoring at short intervals and hence on a continuous basis is best performed through automation. A means for automated inspection of civil infrastructure can be provided through flying robots in terms of a MAV. Those MAVs are equipped with digital cameras recording thousands of pictures of the infrastructure to be monitored. Those pictures have to be stitched such that a high resolution 3D image of the infrastructure to be monitored is obtained. That this is possible has been shown for a rather complex and challenging real building.

Next steps to further complete the monitoring process includes an automated image stitching process as well as image pattern recognition which will allow damage configurations to be recognized and quantified. This will allow damage tolerance principles to be introduced in structures made of materials as diverse as even reinforced concrete. Monitoring the buildings at frequent intervals will further allow a life cycle tracking document to be established on a digital and visual basis which will provide a next generation tool for modern facility management. With the application of further nondestructive techniques this approach may be further enhanced from a surface-based towards an increasingly volumetric monitoring approach.

REFERENCES

1. Golabi K, Thompson P, Hyman W. Pontis: a network optimization system for bridge improvements and maintenance Technical manual. Publication number FHWA-SA-94-031: US Department of Transportation, Federal Highway Administration; 1993.
2. Brecher A.: Infrastructure: a national priority. Soc Women Eng 1995; 4(16):14–16.
3. Roberts E, Shepard R. Bridge management for the 21st century. Transport Res Rec 2000;1696:197–203.
4. N.N. Bridge Inspection Robot Development Interface (BIRDI), Development of high-tech automatic robot system for bridge inspection and monitoring, Technical report for Ministry of Construction and Transportation (in Korean), 2007.
5. Zhu Z., S. German, I. Brilakis: Detection of large-scale concrete columns for automated bridge inspection. Automation in Construction 19 (2010) pp. 1047–1055
6. Zhu Z., S. German, I. Brilakis: Visual retrieval of concrete crack properties for automated post-earthquake structural safety evaluation. Automation in Construction 20 (2011) pp. 874–883
7. N.N.: Bridge Maintenance Training Manual, US Federal Highway Administration, FHWAHI-94-034, Prepared by Wilbur Smith Associates, 1992.
8. N.N.: NJDOT, Bridge Inspection Work Zone, Setup Guide, 2009 http://www.state.nj.us/ (visited 06/2013)
9. Shibata T., S. Shibata: Summary report of research and study on robot systems for maintenance of highways and bridges, Robot, vol. 118, JARA, Tokyo, Japan, Sep. 1997, pp. 41–51.
10. N.N.: Product Catalog, Paxton-Mitchell Snooper® Series 140, http:// www.paxtonmitchell.com. (visited 06/2013)
11. Oh J.-K., A.-Y. Lee, S.M. Oh, Y. Choi, B.-J. Yi, H.W. Yang, Design and control of bridge inspection robot system, IEEE Int. Conf. on Mechatronics and Automation, Aug. 2007, pp. 3634–3639.
12. Eschmann C., C.-M. Kuo, C.-H. Kuo and C. Boller: Unmanned Aircraft Systems for Remote Building Inspection and Monitoring. 6th European Workshop on Structural Health Monitoring, Dresden/Germany (2012) also available on www.ndt.net (visited 06/2013).
13. Kuo C.-H., C-M. Kuo, A. Leber , C. Boller. "Vector thrust multi-rotor copter and its application for building inspection". to be publish in Proc. of IMAV2013 conference Sept. 2013 Toulouse/France.