Implementation of a Low-Cost RTK Positioning System for Drone-assisted Structural Inspections

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ABSTRACT: Technological developments of unmanned aerial vehicles have been rapid and significant in recent years, and thus the scope of use has increased across a broad spectrum of industries, including the fields of structural and civil engineering. A key part of structural engineering is ensuring that a structure can be inspected during its service life to determine if there is any defect that could diminish its structural integrity. In practice, the procedures involved in such inspections to locate defects can be dangerous, time consuming and expensive to conduct. The aim of this study is to establish a system that is cost effective through use of a low-cost unmanned aerial vehicle with Global Navigation Satellite System technology, hence making the process safer for those conducting the inspections. Using positional technology developed by Emlid, a low-cost solution that can be integrated with a unmanned aerial vehicle has been implemented in order to make this goal achievable. A 3D photogrammetric model can be developed of the given structure with associated positional coordinates without the need for ground control points. External aspects of the structure can be inspected and accurately geo-referenced e.g. for use in a Building Information Model. A systematic workflow was developed to establish the most efficient approach to undertaking surveys or inspections predominately through a method of trial and error. This study provides a unique, low cost solution to current practices and methods and has the potential to influence how structural inspections are undertaken in industry.

KEY WORDS: Unmanned aerial vehicles, global navigational satellite system, structural inspection, photogrammetry, real time kinematics, post processed kinematics

1 INTRODUCTION

Land surveying and setting out is an occupation that has evolved profoundly with regards to the practices and processes followed and the complexity and sophistication of the resources and equipment utilised. Original methods of land surveying often included the use of equipment such as measuring tapes and theodolites. This equipment required a lot of manpower to be utilised in an accurate manner, as well as specialised personnel with sufficient knowledge and expertise. This meant that the process was both time consuming and expensive to undertake.

As with most modern industries, research and development has led to methods followed in land surveying becoming more automated and accurate through advancements towards more sophisticated and precise equipment which in turn reduced the manpower required to conduct surveys, and further thus reducing the cost of conducting surveys and precise positioning procedures.

With regards to the equipment utilised in surveying and setting out, the use of GNSS (Global Navigation Satellite System) equipment is becoming increasingly popular. The efficiency and functionality of GNSS equipment is significantly better than previous setting out tools, however the initial investment required to purchase the equipment and associated resources, operational costs and the cost of maintenance are very high. A single reference Real-Time-Kinematic (RTK) system can cost approximately €30,000 and an NRTK system costing approximately €22,000. This is most certainly the greatest disadvantage associated with these systems. An example of a modern positioning system is illustrated on Figure 1.

Figure 1. Modern base station positioning system.

In recent years some developments have been made in the production and manufacture of more cost-effective solutions to expensive GNSS equipment. As part of this study, investigations will be made into such equipment to determine what kind of technologies are available to use and establish if they can perform as well as the more expensive top of the range equipment.

Automation is becoming more prevalent in many industries also, and the civil engineering, structural engineering and surveying fields are no different as in recent years the use of UAVs (Unmanned Aerial Vehicles) have become significantly more popular. The use of drones can improve productivity in construction as they are beginning to become an alternative to undertaking some mapping and surveying activities that would originally be conducted by a surveyor or engineer.

Since structural inspections and monitoring can often require the use of expensive equipment, highly skilled and trained personnel and significant time to actually conduct, these inspections can be expensive and time consuming to undertake [2]. The reason these inspections are so time consuming is also related to the safety aspects of scaling high structures and setting up equipment for inspecting features such as the underside of bridges etc. Drones can however offer a much more efficient and safe solution to inspecting such structures, by making use of the high-power imaging devices they are equipped with.

An opportunity to develop a system that provides a means of conducting structural analyses using drones which utilise highly accurate GNSS positional data to correct the exact position of the structure being analysed has been recognised. This study will be unique as the system developed will constitute the use of cost efficient equipment, to determine if these low cost solutions can perform sufficiently to provide an accurate positioning system for use in industry, improve efficiency by reducing task times and improve safety by reducing the need for site engineers and surveyors to undertake high risk activities. As a result of all of these benefits, the study also targets a reduction in the overall financial cost of projects requiring geo-located building inspection data.

2 METHODOLOGY

2.1 *Description of the Resources Utilised*

Since the scope of this project involves the use of low cost GNSS technologies, investigations were conducted into different resources available that fit under this category. Emlid [3] positioning equipment presents itself as the most suitable for conducting the testing due to its low initial and operational costs.

The Emlid Reach RS+ has been chosen for use in this project as the single reference base station that will provide the positional data corrections for the GNSS rover that will be utilised. It is a single-frequency GNSS system, supporting L1 carrier phase frequency only, which means it can only communicate with other single frequency GNSS devices as a result. The RS+ has the capability to provide data corrections that facilitate positioning with centimetre level accuracy when used in an RTK system. Real time kinematic systems involve two GNSS receivers, one acting as a base station and one as a moving receiver. The fixed base station is set up over a known location and will receive positional data from the satellites available to it. The base station will correct this data relative to its known location and can then distribute these corrections to any mobile receivers in the vicinity. At the same time, the mobile receiver is observing the same satellites, receiving positional data as well as the corrected data from the GNSS base station.

The Reach M+ is a GNSS device designed for use with UAVs to provide accurate positional data for images captured in UAV surveys. The Reach M+ is also a single frequency system that is compatible with L1 carrier phase frequencies. The module is powered through a 5-volt input, which required the use of an external battery source. The M+ RTK system (Figure 2) comprises of the M+ module itself, a Tallysman antenna to receive satellite data and a LoRa radio for communication with the base station. The antenna does, however, require the use of a ground plane on which it must be mounted to reduce errors and improve the general quality of positional data; this is discussed in section 2.4. Investigations and the development of a system for this were considered during the testing stages. In an RTK configuration the rover is capable of achieving positional accuracies of approximately 7 mm in the horizontal directions and 14 mm in the vertical direction [4].

Figure 2. Reach M+ and LoRa Radio [5].

Emlid positioning systems are unique in many ways, but one that makes them stand out against other products in the market is the fact that these systems do not require a data logger device to control the positioning system. As an alternative, a free application is available online for desktops and mobile devices where the Reach devices and data can be managed called ReachView. For the purposes of this project, the ReachView application will be controlled via a smartphone when undertaking testing outdoors.

As well as these GNSS components, the study required the use of a UAV system capable of capturing high quality images and footage for use in structural monitoring and surveying that can be integrated with the GNSS equipment. The DJI Mavic 2 Pro (Figure 3) was chosen for this due to its capability to produce high resolution imagery with a relatively low purchase price which makes it a suitable choice in accordance with the scope and vision of this study. The Mavic 2 Pro has an excellent camera in the Hasselblad L1D-20c, with 20 MP and 4K video resolution capabilities.

Figure 3. DJI Mavic 2 Pro UAV [1].

2.2 *Emlid RTK System Setup Workflow*

The first steps involved were powering up and accessing the ReachView application using the M+ device. The M+ device was first powered by connecting it to a 5V external power bank, as well as the Tallysman antenna. It is important to note, that on the first set up that the M+ device must be powered up in a location that it can successfully complete a time synchronisation process. This can only be achieved by connecting to a Wi-Fi source or allowing the device to receive satellite information. Since this is the initial set up, the device needed to first be brought outdoors (or the antenna held out through an open window) for a sufficient period of time until the device places itself into hotspot mode after observing satellites to complete the time sync. This allows the user to launch the ReachView application being hosted by the M+ device. No positional data will be available while the device's view of the sky is obstructed. If the rover and antenna are placed outdoors in an area that is somewhat free of obstruction, the antenna should be able to receive some form of positional data and although the quality may not be very high, an approximate solution is possible. This was the first step in beginning to establish the RTK system, as the M+ is now receiving positional data and ReachView is operational. This raw positional data is only accurate to approximately 3-5 m. Table 1 illustrates the three different solution statuses that can be achieved and their associated positional accuracy.

Table 1. Solution status accuracy.

Solution Type	***Single***	***Float***	***Fixed***
Accuracy	3-5 m	1 m	10 mm

By setting up an RTK system however, this accuracy can be improved to centimetre level, as per the information in Table 1. This is achieved by setting up the Reach RS+ as a base station to correct the positional data.

The initial set up procedure was very similar to that which was followed when setting up the M+ device for the first time, with regards to the settings and connections that must first be established to connect to ReachView and install the relevant updates. It is important to note that the RS+ is different from the M+ when connecting to ReachView as it does not need to conduct a time synchronisation process. Once the device is operational, the settings in ReachView must be altered. The first thing that must be established is the method of providing corrections from the base station that the rover will utilise. The method that will be used is a LoRa radio system. This is defined in the Base Mode tab on ReachView. Other settings must also be defined before the connection is established. LoRa is a radio, and therefore a frequency must be defined over which the data will be broadcast from the Reach device. A frequency of 868 MHz was chosen, as it is a value that exists within the LoRa frequency band range of 863-870 MHz. The air data rate will also need to be configured. Higher air rate values provide a more stable connection but reduces the base line significantly. After trialling different values of air data rate, 4.56 kb/s was established as being the most suitable setting. The satellite systems to be tracked also need to be defined, and since GPS and GLONASS are the most well-established systems these will be the only systems that will be tracked. The recommended update rates for these satellites systems is 1 Hz to obtain the best results, according to Emlid [4]. The base station coordinates also need to be defined. For now, the base station will be allowed to establish its own coordinates by selecting average float until a time where a known control point can be established.

Following this stage of calibration, the Reach RS+ is now operating as a base station and should be now occupying a position where it can receive positional data. The Reach M+ can now be powered on and occupy a location outdoors where it too can operate without interference. The controller device can now disconnect from the hotspot that is being broadcast by the Reach RS+ and can now connect to the Reach M+ rover instead. The M+ should be functioning and determining its position from raw satellite data. To allow the rover to receive corrections from a base station, settings for the rover must be defined in the RTK Settings tab. Here, the positioning mode will almost always be kept as kinematic as the rover will rarely ever be conducting a survey where it will be completely static for the duration of the survey. The GNSS select settings will involve choosing the same satellite systems as those the base station will be correcting, which were defined previously.

The GPS and GLONASS Ambiguity Resolution (AR) are important settings to consider. AR involves resolving the carrier phase ambiguities that occur when signal is collected by the receiving device, as these can cause significant errors in the final solution that is generated by the processor. The GPS AR mode will be configured to fix and hold, which was found to produce the best results. GLONASS AR mode should be turned on when the Reach rover is communicating with another Reach device that is acting as the base station for best results. The elevation mask should be adjusted accordingly to account for any obstructions so that they do not impede on the mask projected at this angle. The Signal-to-Noise Ratio (SNR) mask can be kept at the predefined 35º so that only good quality satellites are utilised. Maximum acceleration is not a particularly important parameter at present. It generally just allows the processor to determine what information to negate if the accelerations exceed the predefined value, as rapid fluctuations may occur which can be filtered out of the output solution as they are considered errors. If the M+ is installed on a UAV for flight-based surveys, the acceleration parameter may need to be increased as the drone may move faster than 1 m/s, but it was not altered here.

The update rate is the rate at which the rover will receive corrections. 5 Hz is a sufficient value as every 0.2 seconds the device will receive a positional update. Sometimes using the highest update rate can be excessive and inefficient, but for cases where the device will not be logging at very high speeds, such as when it is mounted on the drone, lower update rates will suffice. 5 Hz will be an appropriate value for this stage of testing and will be changed if required as tests proceed. The settings in the Correction Input tab should replicate those that were input in the Base Mode tab for the Reach RS+ to ensure the connection can occur. The base station and rover have established an RTK system when the SNR chart on the Status menu screen displays both coloured bars (for the rover satellite SNR) and corresponding grey bars (for the base station SNR. This is illustrated more clearly in Figure 4. At this point the device is not operating using accurate corrections, therefore a method of establishing a known control point is required to set up the base over is required.

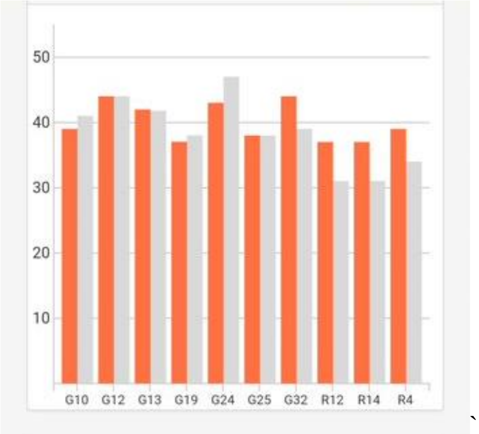


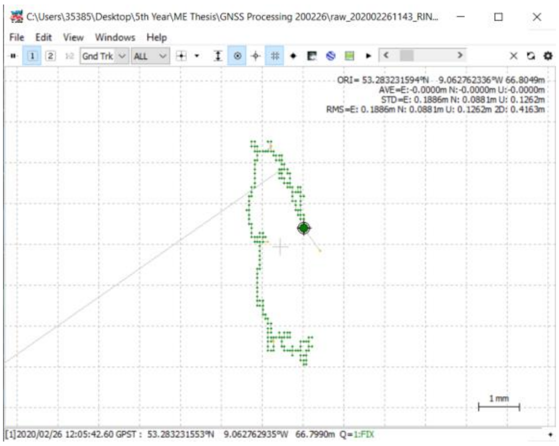
Figure 4. SNR chart displayed for an RTK system in ReachView.

2.3 Establishing a Control Point of Known Coordinates Using the Reach System

A control point of known coordinates can be established using both the Reach RS+ and the information from a local permanent reference station that is operated and controlled by the (Ordinance Survey Ireland) OSI. The data logs that record the satellites observed by the reference station with respect to their position and the time at which they occupied this position are constantly updating and being saved at these reference stations and are available to download online for free. These logs, along with the logs that the RS+ base station records while turned on, can be combined to give a fully corrected solution for the RS+ position using Post-Processed Kinematic (PPK).

A location for the control point was established on the grounds on the NUI Galway campus in front of the Engineering Building. A control point should be placed in a location where it will be free from obstructions such as trees and buildings as much as possible, although this can be difficult in urban areas. The control point should also be denoted in a way that its position cannot be easily altered, therefore some form of peg in the lawns would be unsuitable as it can be easily removed. Once this point was marked, the base station could be erected directly over this pinpoint location and powered up and set up in base mode as before using a tripod and tribrach system to centre the RS+ over the control point. The base will simply be allowed to occupy this point for a fixed period of time so that it can collect positional data in the system data logs. It is important to predefine the file format that the logs will be recorded in. The option to save the raw data can be alternated, and should be switched to "ON", and the output format should be changed to RINEX so that it is compatible with the OSI data logs. These logs are downloaded after the base station has occupied the control point for a sufficient period of time. The local reference station used to correct the position is located 300 m from the test site, so errors are minimised. Once both data sets are downloaded a method of undertaking the correction process needs to be established. PPK is a method of providing a UAV GNSS device with corrections after the flight has taken place rather than during the flight. This method can be applied in this scenario to provide corrections using the raw data obtained by the RS+. This procedure can be undertaken using a free to download software called RTKLib, which uses an application called RTKPost to conduct the post processing of the two data logs to output a corrected positional solution.

To begin the analysis, the time and date which the data relates to should be first input at the top of the dialog box. This is important, as the system will only correct data that occurs between the times on the stated date. Once this is correctly specified, the two sets of data logs are imported in the RINEX OBS fields. The RINEX OBS: Rover will be where the RS+ logs are imported, as it is the RS+ which is acting as the "rover" to be corrected. The RINEX OBS: Base Station will be the logs from the reference station are added. There is also the option to add a .nav file in the command space below this. A .nav file details the navigational satellites that were observed by either the rover or the base station which helps to improve the accuracy of the final solution. Finally, the last step is to simply direct where the user wants the output positional file to be stored in the computer's files, which is defined in the Solution command window at the bottom. The results are then obtained by pressing execute. The results can also be plot in RTKPlot directly from the RTKPost application by pressing the plot option at the bottom of the screen. The result is illustrated in Figure 5 below.



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C:\Users\35385\Desktop\5th Year\ME Thesis\GNSS Processing 200226\raw_20200261143_RIN...
ORI= 53.283231594°N  9.062762336°W 66.8049m
AVE=E:-0.0000m N:-0.0000m U:-0.0000m
STD=E: 0.1886m N: 0.0881m U: 0.1262m
RMS=E: 0.1886m N: 0.0881m U: 0.1262m 2D: 0.4163m
[1]2020/02/26 12:05:42.60 GPST :  53.283231553°N   9.062762935°W   66.7990m  Q=1:FIX
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Figure 5. Precise location of the control point found using *RTKplot*.

The control point established was found to have coordinates of 53.283252 N, -9.062763 E and an elevation of 65.252 m.

2.4 Ground Plane Trials

A ground plane is required to reflect radio waves, improve the signal reception and it also helps to reduce the occurrence and significance of multipath errors [6]. The size of the ground plane is quantified based on the length of one quarter of the wavelength radius, which is 70 mm when operating at approximately 900 MHz. Therefore, the dimensions of such a ground plane for the Tallysman antenna should, be made to at least these dimensions [6]. To make a strong inference on the significance of including a ground plane for an antenna in a positioning system, a short and rather simple test was carried out. The Reach M+ system was powered on and the Tallysman antenna was attached to it. The system was setup on top of a car roof, but a book of A4 sheet size dimensions was placed underneath the antenna, so that it was not in contact with the conductive metal roof of the car. The system was allowed to log data in this configuration for approximately 10 minutes.

Following this, a piece of aluminium foil approximately 100 mm square in dimensions was centred under the antenna while still on the book, and as before was left for approximately 10 minutes to log data. Aluminium foil is suitable for use as a ground plane, as the material needs to be at least 5 times thicker than the skin depth of the material being used, which is 0.82 µm for aluminium, and five times this is 4.2 µm. The thickness of a piece of aluminium foil is at least 16 µm, and therefore is suitable for use as a ground plane [7].

Using PPK, the results were examined and showed that the inclusion of a ground plane improved the position dramatically, with the position without the ground plane located over 1 metre from the placed position.

A bespoke ground plane was then constructed for the M+ antenna so it could be integrated with the DJI drone. The component was constructed of timber with a sheet of aluminium foil placed on top of the device so the antenna could be positioned on it.

2.5 *Integration of the Reach M+ and Mavic 2 Pro by Conducting a Survey of a Building*

One of the most important aspects of this study was the aim to establish a method of correcting the positional coordinates applied to images obtained with a UAV for the purposes of structural monitoring and surveying. A form of correcting positional coordinates using a low cost RTK positioning system has been established at this point in the study, and to achieve the aims set out at the beginning of the study a test must be carried out using this system with a UAV.

The test site for the penultimate test was originally planned to take place at the front of the NUIG Engineering Building but was changed to the NUIG Sports complex at Dangan, on the north of the campus. Here, the rear of the complex building was analysed for the purposes of the survey. Due to the change in venue, the Reach RS+ base could not be utilised as there were no known control points in the area, as well as a restriction on the access to equipment also.

The Reach M+ device was powered using the external battery pack that was to be integrated with the drone as well as a ground plane component. The drone was powered on and the synchronised with the DJI GO application to view the images being captured by the camera. The antenna was placed on the ground plane and supported by hand on the front of the drone, with the antenna fixed in a manner that it was centred over the top of the camera as accurately as possible.

The survey simply involved holding the Reach M+ system on the Mavic 2 Pro and capturing an array of images along the rear of the complex building. The array of photos obtained were subsequently utilised to generate a photogrammetric model using Autodesk ReCap in the data analysis stage. With each image there will be an associated positional coordinate that was obtained by the Mavic 2 Pro. The M+ positional data was corrected using PPK as before. The quality of the data was not ideal, with a significant proportion of the data only achieving float point status. The positions of the images from the drone were then matched with the times that coordinates were found from the corrected M+ positional data. Figure 6 shows the PPK solution overlaid on an aerial map in Google Earth.

Figure 6. PPK solution from the survey of the Dangan sports complex.

The corrected positions were applied to the images captured by the drone in a software called Exif pilot [8]. The images were then ready for processing in a photogrammetric software to create a 3D geolocated model using AutoDesk ReCap Photo [9]. When the images were corrected it was important to note that the elevation offset (45 mm) between the centre of the camera lens and the bottom of the M+ receiver was subtracted from the heights to compensate for this elevation difference.

3 RESULTS AND DISCUSSION

The accuracy of the system is of interest to determine if the improvements and developments to this point have performed as expected. This can be demonstrated by comparing the standard deviation of the three coordinates that make up a point observed at a particular time. 60 seconds of data was compared, by taking the average of the three standard deviations over the 60 seconds for both the corrected and uncorrected solutions, the overall average in each coordinate direction can be determined. The 60 seconds that were examined were between 14:37 and 14:38 on the day of testing, and of the 60 recordings, 53 obtained a positional fix when corrected and 7 obtained a positional float. The summary of this test is illustrated in Table 2 below.

Table 2. Comparison of corrected and uncorrected data.

	Average standard deviations		
	latitude(m)	longitude(m)	height (m)
Corrected	0.0139	0.0133	0.0280
Uncorrected	1.8669	2.7338	5.2276

The result was swayed slightly due to the 7 float coordinates, and without these, the results would have been 9.5 mm, 6.3 mm and 15.3 mm respectively.

The 3D photogrammetric models that were returned were of average quality, due to the fact that the drone could not be flown to acquire aerial images. Figure 7 below illustrates an example of model constructed.

Figure 7. Photogrammetric model of the surveyed building.

The incompleteness on the roof is evident from this image. There was a further issue noted that AutoDesk ReCap does not recognize smartphone images in the geolocating process, and several were utilized in the study, preventing full geolocation of the building. To demonstrate the significance of aerial images, a trial was conducted using a smartphone and an array of concrete blocks, where aerial images could easily be obtained on foot. The images were compiled in ReCap and a photogrammetric model was constructed. The model came out in excellent quality, and the requirement for aerial images as well as terrestrial images proves significant. The position of camera during this process was also tracked using a Reach M+, and the post processed results are illustrated in Figure 8 which indicates the path that was followed when conducting the analysis.

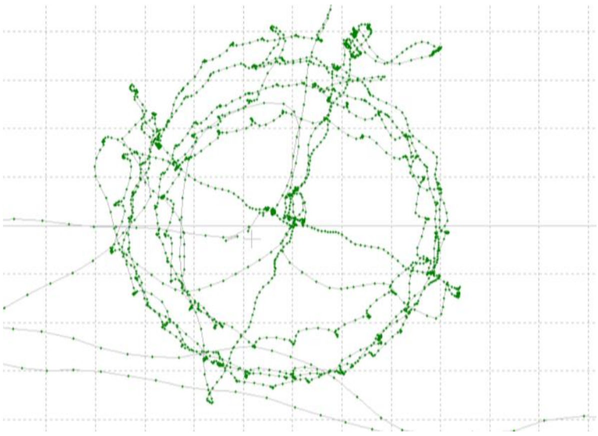

Figure 8. Post processed results plotted in *RTKPlot* of the analysis of the blocks (The track used was approx. a 2.5 m diameter circle orbiting the block structure at the centre).

The result was highly accurate, with over 90% of points achieving fixed positional status with high levels of accuracy (sub centimetre level).

The task of creating 3D models using images obtained from a UAV with positional corrections applied to the images has been somewhat achieved at this stage of testing. The issue of not being able to obtain aerial images using the drone did reduce the quality of the model output; these aerial images would allow a much more accurate and well rendered model of the Dangan sports complex building to be obtained.

4 CONCLUDING REMARKS

The low-cost technology utilised in this study would enable a wider adoption and integration of GNSS and UAV systems, supporting the next stage in these advancements in the industry, with the use of UAV devices driving many tasks closer to semi, or full, automation. Year on year, the scale of developments in the construction industry are increasing, with the size of newly built structures growing significantly, and the time that these structures are erected and constructed at constantly decreasing, with growing efficiencies. These developments put a greater strain on those working in the industry to perform their duties in both a safe and timely manner, as one human can only work so fast. Due to the growing popularity of photogrammetry, there may be other 3D photogrammetric modelling programmes that do allow the construction of geolocated models from smartphone images. Some studies have been conducted which involve the use of ground con troll points, and the results indicate that a significant number of ground control points which requires the use of accurate positioning systems and can be very time consuming [10]. The use of corrected smartphone images is also an option, however research in this area is minimal as smartphone image GNSS data is generally uncorrected and there has been little investigation conducted on correcting smartphone image GNSS data for photogrammetric modelling. Smartphone GNSS accuracy is too poor to utilise it for accurate located 3D photogrammetric models [11].

The alternative in situations where smartphone images are utilised in modelling whereby geolocations are to be applied to the model is by using GCP’s (Ground Control Points). This is however a time-consuming process and requires several GCPs to be installed for high levels of accuracy, which thus requires the use of highly accurate GNSS positioning technology [11]. The use of GCPs is useful for obtaining accurate coordinates in a 2D plane, however in the vertical plane the accuracy is much less. Accurate RTK systems can be more accurate in this instance.

The tasks and business of undertaking structural surveys on both small and large structures can be difficult and dangerous not to mention being a costly service which makes use of equipment which is also expensive. The investigations conducted here have contributed somewhat to establishing a system that will provide a stepping-stone in the advancement towards making the growing inefficiency of the tasks of structural inspection, monitoring and setting out a thing of the past. But, with some further consideration, testing, research and developments, an idyllic industry-suitable solution will be available in the near future.

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