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Low Cost Vision Based Personal Mobile Mapping System

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ABSTRACT:

Mobile mapping systems (MMS) can be used for several purposes, such as transportation, highway infrastructure mapping and GIS data collecting. However, the acceptance of these systems is not wide spread and their use is still limited due the high cost and dependency on the Global Navigation Satellite System (GNSS). A low cost vision based personal MMS has been produced with an aim to overcome these limitations. The system has been designed to depend mainly on cameras and use of low cost GNSS and inertial sensors to provide a bundle adjustment solution with initial values. The system has the potential to be used indoor and outdoor. The system has been tested indoors and outdoors with different GPS coverage, surrounded features, and narrow and curvy paths. Tests show that the system is able to work in such environments providing 3D coordinates of better than 10 cm accuracy.

1- INTRODUCTION

1.1 Background

The main industrial driving force behind the development of MMS has been the need for highway infrastructure mapping, transport corridor inventories and track side surveying. However, these days, MMS is widely used in several areas, such as transportation, emergency response, 3D city modelling, tourism, engineering applications and collecting geographical information system (GIS) data. During the last two decades, rapid developments in MMS have been recorded and what started as an academic design concept have become a reality and an industry (Tao and Li, 2007).

Almost all MMSs have been designed to depend mainly on GNSS and an inertial navigation system (INS) integrated for geo-referencing the imaging and/or laser scanning sensors. Therefore, the accuracy of MMS has increased hand-in-hand with increases in the accuracy of navigation sensors. Today, dual frequency GPS receivers, tactical inertial measurement units (IMUs), high resolution cameras, advanced sophisticated processing techniques and additional sensors, such as odometer, barometer and inclinometers are all used in MMS to provide potentially centimetre accuracy of platform positioning and sub metre level 3D object space coordinates (OSCs). However, this can lead to the overall cost of such a system to be significant which restricts the widespread adoption of the system in the survey industry and ultimately limiting its use in applications (ibid).

Different designs have been produced for MMS to overcome the high cost and GNSS dependency. These have included using low cost navigation sensors, using 3 GNSS receivers for orientation measurement instead of the IMU and using the integration of image based navigation and INS (Williams, 2006). However, it is hard to depend on low quality navigation sensors when trying to achieve accurate 3D OSCs. Meanwhile, using 3 single frequency GPS receivers to determine orientation can provide only limited

accuracy and using dual frequency receivers is not cost-effective. Either of these options continues to give an over reliance on GNSS. Using a low cost IMU can overcome the reliance on GNSS but suffers from excessive sensor measurement drift. Adopting image based navigation can be used to aid the control of the IMU drift. Image based systems are often based on image matching and when this is lost, the IMU can be used to control the quality. When the highest accuracies are required it may be necessary to use a tactical grade IMU sensor.

In general, MMSs have become important in several applications but their need for vehicle access can restrict their use to highways, railway tracks or near shore marine routes. The limitations on flexibility of movement and the high cost of tactical grade inertial systems and survey quality GNSS equipment has led to consideration of a personal vision based mapping system using small size and low cost sensors.

1.2 Aims and Objectives

This project aims to design a low cost vision based personal MMS using a 'human' mobile platform requiring only walking access to the area to be mapped. The main objective is to undertake a proof of concept study and an assessment of the potential object point geo-referencing quality. This led to the following objectives being investigated:-

1. Design a prototype system.
2. Undertake trials to establish the operational procedures and the quality of object point geo-referencing.

1.3 Methodology

The methodologies used for fulfilling the objectives and assessing the system are:

- 1- A system design based on literature review and experience of sensors and integration.
- 2- Establish a test site(s) for trials to be undertaken.
- 3- Undertake trials:-
 - a. Using check points along trajectories.
 - b. Using the exterior orientation parameters (EOPs) obtained from Australis 7 with many ground control points (GCPs) and manual image matching (bench mark, reference) to evaluate the low cost navigation sensors used in the system.

2- SYSTEM DESIGN

2.1 Description and Equipment Assembling

The designed system, named 'M2CN' consists of data logger, three off-the-shelf digital cameras (2 Nikon D200 and 1 Nikon D300), Microstrain 3DM-GX3-25IMU, u-blox 6 GPS receiver, distribution box, antenna splitter, battery and GPS antenna. The data logger is used to record the readings from the navigation sensors and capturing time for each camera in the GPS time frame. The operator presses the trigger on the data logger which sends a pulse to the cameras via the distribution box to record an image.

The cameras take pictures when receiving a pulse and send a pulse back to the data logger when finished the imaging process. An antenna splitter is used to connect the antenna with GPS receiver and provide the antenna with the necessary power. The battery is used to power the IMU, GPS receiver and to charge the data logger when necessary, see figure 1.

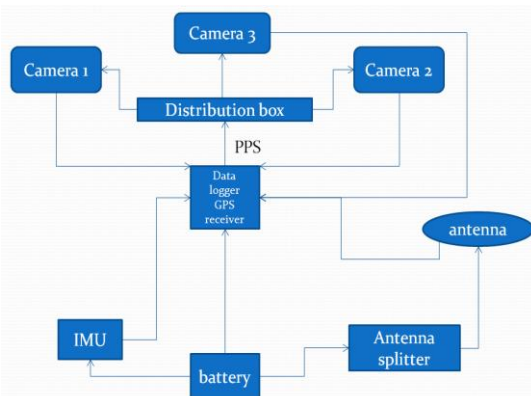


Figure1. M2CN: Equipment diagram

The equipment can be assembled in many physical designs to suit the area of interest. For example two cameras can be positioned one above the other or horizontally as shown in figure 2. Two important points should be considered in the design:

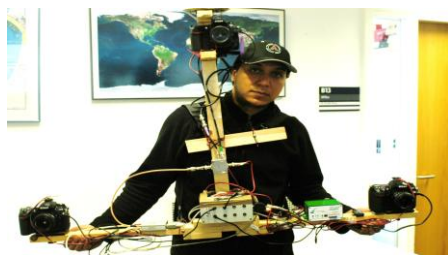


Figure 2. M2CN (Horizontal design)

- 1- The need to keep the distance between the two baseline cameras as bigger as possible for better intersection angles. This is important particularly for objects far from the camera which can produce unstable geometry.
- 2- Introducing a third camera to form a triangle helps to identify erroneously matched image points using a multi-coplanarity condition.

2.2 M2CN: Operational Design Concept

The operational design concept is illustrated in figure 3 and can be summarised in the following points:

- 1- The trajectory is divided into 'stations' each station includes three synchronised images, one from each of the three cameras.
- 2- The three images at each station are matched automatically to find common image points.
- 3- The matched points are filtered using multi-coplanarity condition based filter (discussed in section 3.1). From these matched points, only well distributed points with good intersection angles are chosen.
- 4- The common image points from each station are matched with those of next stations to find common points between as many images as possible. These are then considered as blocks.
- 5- Now the trajectory is divided into blocks each one includes two consecutive stations. For example block 1 includes stations 1 and 2 and block 2 includes stations 2 and 3. So, station 2 is overlapped between the two blocks.
- 6- With the help of at least 3 GCPs, the EOPs of the first station images are determined and used to update the IMU rotations and the GPS relative positioning technique used in the system (temporary double differencing carrier phase (TDDCP)). This helps to limit the cumulative errors. Kinematic carrier phase DGPS (KCPDGPS) and stand-alone GPS are other techniques available with the system which give initial absolute camera positions.
- 7- Indoors or when GNSS is absent, a linear station positioning method (LSPM) is used for predicting camera positions which creates a vector equation from the previous two positions.
- 8- The low cost navigation sensors are used to provide the bundle adjustment solution (BAS) with initial EOPs for the images of second station.
- 9- Approximate values for the OSCs of the determined common points are calculated using space intersection.
- 10- All the observations of the first block are processed in a self-calibration bundle block adjustment (SCBBA) to calculate the EOPs of the images at the second station.
- 11- The EOPs of images at the second station are used for updating the navigation sensors which are used to determine approximate values for the EOPs of the images at the third station.
- 12- The same steps are repeated for the next second block where the EOPs of images at the second station are regarded as fixed while the EOPs of the images at the third station are determined.
- 13- The same procedure is repeated for all blocks.
- 14- Finally, the results of all blocks are bundled together in one SCBBA considering just the EOPs of images at the first station as fixed.
- 15- Additional GCPs can and should be used at the end of a long trajectory for more reliable results. The other

alternative solution is to use a closed loop with common points at the two ends of trajectory.

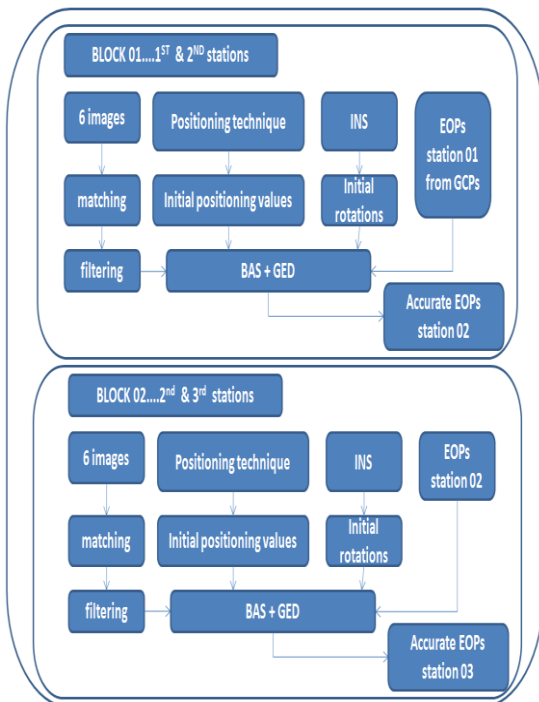


Figure 3. M2CN: operational design concept

3- SOFTWARE DEVELOPMENT

M2CN-Centre is a Matlab algorithm developed for M2CN system to carry out the main tasks. M2CN-Centre provides a friendly graphic user interface. Figure 4 shows the main window which includes the following:

- 1- Calculating Euler angle from IMU raw data.
- 2- Calculating TDDCP positioning.
- 3- Transformation from Euler angles to (ω, φ, k) .
- 4- Linear positioning.
- 5- Automatic image matching.
- 6- Matched point filtering.
- 7- Compute approximate values for OSCs.
- 8- BAS.

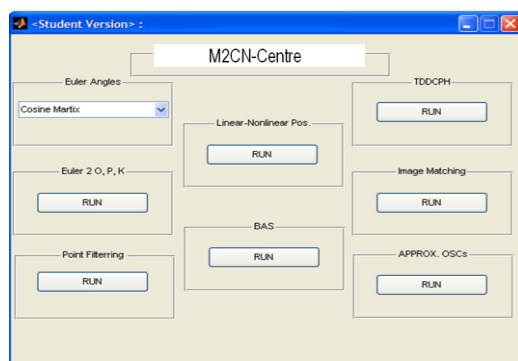


Figure 4. M2CN-Centre main user interface

BAS has a sub graphic interface. The function of BAS is provided with different options including:

- 1- Optical axis direction: aerial and terrestrial photogrammetry.

- 2- Additional parameters (AP) model: 6 AP, 7 AP or without AP.
- 3- Rotation matrix including three options compatible with Leica Photogrammetric Suite (LPS), Australis 7 and 3DB algorithm.
- 4- Number of iterations and convergence value.
- 5- Image coordinate transformation: converts image coordinates from corner based system to centre based system.
- 6- Units of the resulted rotations (degree or radian)
- 7- Converting ω, φ, k to Roll (Ro), Elevation (El)(pitch), Azimuth (Az)(yaw),
- 8- Run BAS as: combined, observation or condition equation.
- 9- Final statistical report and gross error detection.

3.1 Automatic Image Matching and Filtering

Speeded Up Robust Feature (SURF) is adopted in M2CN for image matching. Tests show that SURF can provide excellent automatic image matching with sub pixel accuracy. However, this algorithm has some limitations which had to be considered before it can be implemented in M2CN, these are:

- 1- No more than two images can be matched simultaneously.
- 2- Slower processing with high image resolutions.
- 3- No filter for mismatched points.

To find common points between several images, the interest points of each image are detected and described using SURF detector and descriptor (Evans, 2009). Then the description vectors of the interest point in each image are matched with those in the other images giving the common tie points between all images. This procedure is followed to increase the number of equations giving more redundancy for the BAS.

SURF is very fast with low image resolutions but slows with higher image resolutions. SURF has been modified to be faster by using image pyramids. The interest points in any image will still appear after resample of the image. So, resampling can be used to reduce the size of images and increase speed of processing. To speed up SURF, the images are firstly resampled and matched with the new low resolutions. Then, the approximate positions of the matched points are determined on the high resolution images. Sub images are created around the approximate positions on the high resolution images. Finally, each two corresponding sub images are matched giving the final common points. This helps to reduce the processing time significantly where just a number of small images are matched instead of matching the whole images. This idea has been applied with different resampling levels, numbers of points and different image sizes giving significant differences in processing times as shown in figure 5.

The common points between the three images of each station obtained from the modified SURF tend to have some mismatched points as shown in figure 6 (top). As the ROPs between cameras are fixed, the mismatched points between each two images can be filtered based on the coplanarity equation. However, this condition cannot deal with the mismatched points located in the direction parallel to the cameras baseline. For this reason the system has been

provided with three cameras to use the multi-coplanarity condition based filter for detecting the mismatched points.

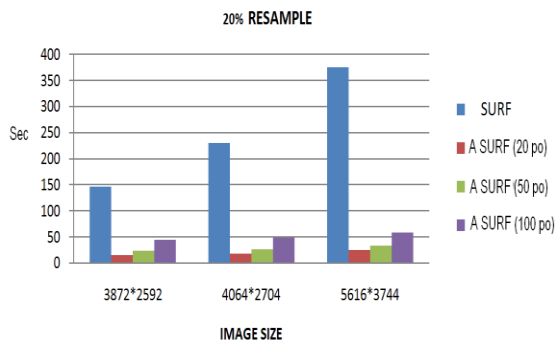


Figure 5. Processing time: SURF VS. Image pyramids based SURF with different number of matched points. (Image size in pixels, po = number of points)

Three coplanarity equations are used in this filter, namely: between images (1, 2), (1, 3) and (2, 3) as illustrated in figure 7. The first coplanarity condition detects the mismatched points in y direction between image 1 and 2. The second condition of image 1 and 3 filters the mismatched points in all directions except those parallel to the baseline of the two cameras. The same is for the third coplanarity condition of image 2 and 3. Passing the three conditions means that the three points are correctly matched where this filter is based on clear mathematical conditions. However, a range of flexibility should be added to the condition duo to the small errors in the inputted ROPs and IOEs and image coordinates.

After this step, the role of the third camera is finished and just two images at each station can be used for faster BAS. The resulted points with small intersection angles are then removed and just the well distributed points in the images are chosen automatically to be used in the BAS. Figure 6 (bottom) illustrates an example of the final filtered results.

3.2 Bundle Adjustment Solution (BAS)

BAS is one of the main functions developed under M2CN-Centre to solve the collinearity equations and relative orientation equations (ROEs) together. Using ROEs help to make the geometry more robust and stable. Taylor series is used in linearizing the equations. The general formula of combined equation is: (Cross, 1983).

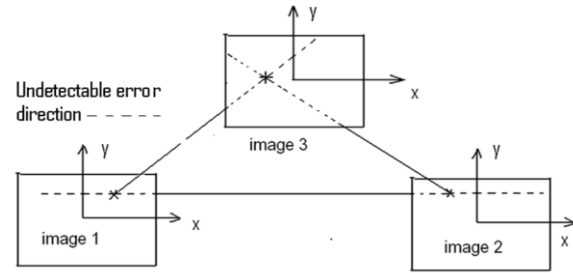


Figure 7. Multi-coplanarity condition based filter

$$A_{(e^*p)} \times x_{(p^*1)} + C_{(e^*o)} \times v_{(o^*1)} - b_{(e^*1)} = 0$$

Where, matrix A and C are ‘design’ matrices (includes the partial differentials), vector x includes all the parameters, vector v are the residuals and vector b includes the differences between observed and computed values. The number of equations, parameters and observations, are e, p and o, respectively.

The solution is iterative, terminating when convergence or maximum number of iterations is reached and statistical report is provided for the final solution.

4- SYSTEM CALIBRATION

Calibrating the system is an important step for achieving reliable results. Calibrating the system includes four steps, namely: camera calibration, determining the ROPs between cameras, the GPS-camera lever arms and the camera-IMU misalignments.

Australis 7 has been used with the calibration frame at Nottingham for camera calibration. The cameras should be adjusted to have common shutter speed, ISO sensitivity and aperture size to provide high quality images in different brightness levels, moving speeds and vibrations. The three cameras have been fixed on the system frame and connected to the data logger and the distribution box. Synchronised images have been taken of a number of targets and Australis 7 has been used to determine the ROPs between the three cameras. To provide these values with correct weights in BAS, the test has been undertaken several times enabling a mean and the standard deviations of each element to be determined.



Figure 6. (top) SURF without filtering; (bottom) final common points using the modified SURF

In order to measure the GPS-camera offset, a total station has been used to coordinate the geometric centre of the GPS antenna. Then, synchronised pictures including fixed targets in the surrounding area have been taken from the three cameras. Australis 7 has then been used to determine the position of each camera relatively to the fixed points. The differences between the cameras perspective centres and the GPS antenna have been determined giving the GPS-camera offsets. The camera-IMU misalignment has been determined using measurements in the Auto-Cad software. Two images (top and side view) have been taken of the camera and the IMU. Then, lines between the IMU corners and the camera have been drawn and the angles between lines have been used as the misalignments. Figure 8 shows this misalignment using Auto-Cad. The calculated offset and misalignment values may be of limited accuracy, where the antenna geometric centre is not the antennas physical centre and the external angles of the camera may not parallel to those of the CCD. However, they were shown to be adequate for the purpose of providing approximate values for the BAS.



Figure 8. Camera-IMU misalignment

In M2CN, the camera axes, namely: x, y and z are corresponded to Y, X and -Z axes of the IMU, respectively. Therefore, the IMU Euler angles, namely Roll, Pitch and Yaw can be used directly as φ , ω and κ in this order after applying the misalignment corrections.

5- M2CN: TESTING AND EVALUATION

5.1 Testing Sites Description

M2CN has been tested in various indoor and outdoor areas with different: surrounded features, types of paths, images intervals, number of images and camera baselines. Presented here are the results from two trails; one is an outdoor reasonable good GPS environment and the second is a demanding indoor environment. Table 1 gives details of the two tests in terms of GPS coverage, type of surrounded features, type of paths, image intervals (ImI), distance coverage (DC) and number of images used from the 3 cameras (IN). Figure 9 shows the test sites.

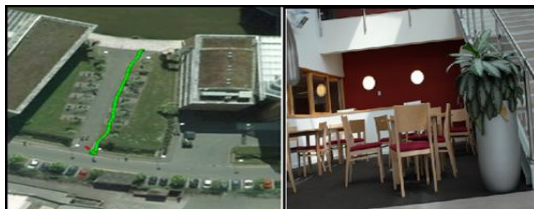


Figure 9. Test sites

5.2 Results and Discussion

5.2.1 Manual Matching Results

The images have been firstly matched with manual tie, control and check point measurements using Australis 7 with

a considerable number of GCPs. More than 20 check points have been used for each test to evaluate the quality and Table 2 illustrates the results.

Table 1: Tests description

GPS	Features	Path	ImI (m)	DC (m)	IN
Reasonable	Mixed	≈ Straight	4	85	36
No	Reflective mixed	Sloping & Very curvy	Mix	90	69

Table 2: Check point RMSE from the manual matching test

RMSE	X m	Y m	Z m
Test 1	0.032	0.023	0.021
Test 2	0.049	0.034	0.027

Table 3 shows that 3 cm RMSE in average can be achieved for OSCs with camera-to-object range of nearly 15 m. The errors of the check points can be attributed to the error in: GCPs, IOEs and the manual matching procedure. For accurate evaluation, the same check points will be used to evaluate the system with automatic matching. The errors in the obtained EOPs is theoretically much less than that of the resulted OSCs. Therefore, the obtained EOPs will be used as references to evaluate the performance of the low cost navigation sensors used in the system. Figure 10 shows the curvy slope path of the indoor test using Australis 7.

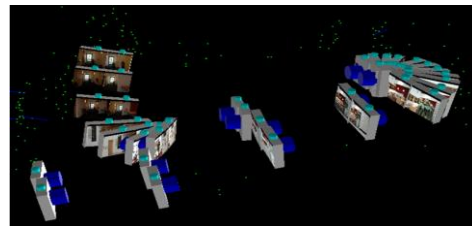


Figure 10. Test site 2: curving, sloping path

5.2.2 Evaluating the Positioning Techniques.

To evaluate the four positioning techniques available with the system, namely: TDDCP, KCPDGPS, stand-alone GPS and LSPM, the camera perspective centres derived from these methods have been compared with those obtained from the manual matching results. As the first test has been applied outdoors, all techniques can be used where the first three methods are GNSS-dependent. However, in the second test, just LSPM has been available. Table 3 illustrates the results.

Table 3: GPS coordinates compared with the camera manual matching results for the Perspective centre coordinates

RMSE	X m	Y m	Z m
TDDCP	0.052	0.082	0.118
KCPDGPS	0.095	0.101	0.235
Stand-alone GPS	0.758	0.915	2.367
LSPM (Test1)	0.141	0.091	0.065
LSPM (Test 2)	0.438	0.682	0.354

It is clear from the table that TDDCP has given the best 3D accuracy with nearly 10 cm. TDDCP is regarded as the most accurate method for obtaining positioning from stand-alone single frequency GNSS receivers where the ionosphere and

troposphere delays, satellite orbit and clock error and receiver clock errors are mitigated (Black, 2006). Furthermore, with regular updating, the cumulated errors tend to be minimized if avoiding the multipath effect. Using carrier phase, in general, reduce the effect of the multipath to be within the half of the cycle (nearly 5 cm). To mitigate the effect of the reflected signals, which tend to have left hand circular polarisation, GPS antenna with right hand circular polarization has been chosen to be used with the system. KCPDGPS has also given good and continued solution (no cycle slips). This can point to the low effect of multipath in the test area where the high multipath can affect the correlation between the direct signals and those generated by the receiver and thus the connection might be lost resulting in cycle slips. LSPM has provided accurate results in the first test where the intervals between the stations are nearly constant and degraded to some extent in the second test with mixed and irregular intervals. Code positioning has been the poorest in terms of accuracy due to the common errors of stand-alone GNSS solution.

5.2.3 Evaluating the IMU Sensor

Tests show that the IMU used in the system has provided rotations to an accuracy of 2 to 3 degrees using raw data with regular updating of 10 sec from the photogrammetric solution. The magnetometer based corrections have been neglected in the instrument to avoid the adverse effects of the magnetic field generated by the surrounded equipment. For better accuracy, the average rate of gyro drift can be calculated when the sensor is stationary (10 to 20 sec are enough) and used as liner corrections when the sensor moves. The accuracy with this simple filter has reached the level of nearly 1 degree with gyro drift of nearly 0.1 degree/sec. Figure 11 gives an example of pitch rotation and compares the IMU rotations with and without corrections

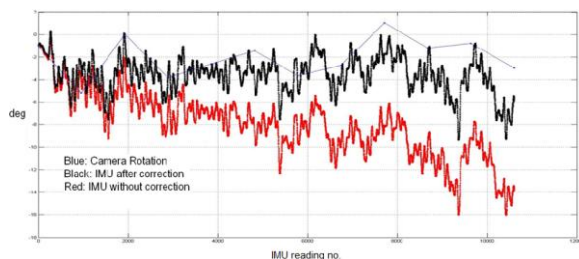


Figure 11. Example of pitch evaluating the IMU performance

with those derived from the camera.

5.2.3 Automatic Matching and BAS

The tests show that the modified SURF with the multi coplanarly conditions based filter has provided correctly matched points even in difficult areas with reflective surfaces, similar features and nearly monochrome colour. The main problem faced during the tests has been the high pedestrian density where areas of the image might be covered by closely passing bodies causing the automatic matching to fail. This can be overcome by extra station images being taken to enable some to be rejected. In the first test with nearly a straight path and small image intervals, common points between several stations have been detected making the geometry robust. In the second test, more images have been used with curvy path to guarantee the overlapping between images and the links between several stations. Tests show that the SCBBA has converged within a

few iterations due to the good initial values obtained from the positioning techniques and the rotation sensors. Furthermore, adding the ROEs to the collinearity equations have helped the solution to be more stable even with large numbers of images. Test show that, as expected, the bigger the camera baseline, the better accuracy and the more stable geometry can be achieved. The camera baseline has also an effect on the image intervals where the smaller the camera baseline, the small image intervals and consequently more images are needed. To evaluate the system performance, the same check points used for evaluating the results of Australis 7 have been used to assess the accuracy of the system. Table 4 illustrates the results.

Table 4: Evaluating the system Check point coordinates

RMSE	X m	Y m	Z m
Test 1	0.076	0.054	0.047
Test 2	0.084	0.073	0.075

From table 4, the 3D coordinates have an RMSE of less than 10 cm in each component. Part of these errors can be attributed to the manual measurement of the check points on the images where an error of several pixels is expected and the ground resolution is nearly 0.5 cm with 15 m camera-to-object range. As might be expected, the RMSE in the direction of the optical axis is relatively the worst, as in the first test. However, with curvy trajectory, the optical axis changes from X to Y leading the RMSE in the two directions to be close in test 2. The results of the first test have better RMSE than the second. This can be attributed to two main reasons; the first is that with straight path, common points between several stations have been detected making the geometry more robust and consequently better results have been obtained. The number of images can also affect the quality due to the propagation of the errors, especially without linking multi images together as in the case of curvy paths.

6- CONCLUSION

The low cost vision based personal MMS has been introduced to overcome some limitations of the conventional MMS, namely the high cost and the high dependency on GNSS. Tests show that M2CN can present levels of quality that make the concept fit for some applications. M2CN can be used to complement the conventional MMS in the areas not easy to access by conventional vehicle based MMS, such as between buildings and indoors. Further trials are being undertaken to full understand the systems potential.

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