MoRe-T2: An easy-to-use, low cost tracking system for mobility research

Chinemelu Ezeh, Catherine Holloway, Tom Carlson
University College London, London, UK
chinemelu.ezeh.14@ucl.ac.uk
c.holloway@ucl.ac.uk
t.carlson@ucl.ac.uk

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Abstract

Measuring how difficult access is for people is important in order to achieve inclusive access for all. One practical and effective way of measuring difficulty in people's access is to track how they move around in a given environment. However, systems for tracking people are often costly and complicated to use. This article concerns the development and application of a low cost computer vision-based tracking system called MoRe-T2 (mobility research trajectory tracker). MoRe-T2 can be used to quickly characterize the trajectories people make under different conditions (e.g. when using a wheelchair, exiting through a train's sliding doors, approaching a ramp or moving through crowded environments). A MoRe-T2 system uses video cameras such as a webcam to track the pose of QR-code-like markers. MoRe-T2 markers enable orientation as an extra level of tracking information and they uniquely identify many participants. Both of these features of a marker are unavailable in markers of more standard techniques for video tracking like 'blob' detection (i.e. simply tracking a blob of a certain colour for example). These markers can be simply printed onto paper and can then be attached to people or assistive technologies, such as a wheelchair and a scooter. The MoRe-T2 cameras are time-synchronized and are mounted so that at any given time every marker in the experiment area is visible to at least one camera. In a simple process, the cameras' positions can be sufficiently estimated automatically using a single marker. Videos of the scene are recorded and afterwards, the recorded videos are processed with the cameras' estimated position using software called ARToolkitPlus library. This software calculates the position and orientation of markers with respect to the cameras. The end result is a detailed map describing the time-locked trajectories plotted on a 3D time independent plane.

Keywords: Tracking tool, computer vision, mobility assessment, people-tracking, trajectory reconstruction

Introduction

In accessibility studies that aim to achieve inclusive access for all, the motion people make under different conditions (e.g. when using a wheelchair, exiting through a train's sliding doors, approaching a ramp or moving through crowded environments) need to be studied and characterised. Huber et al., 2014's work on obstacle avoidance strategies in human walking behaviour using the Vicon motor system to track trajectories made by participants, is an example of a study on a motion of interest. Existing motion-tracking systems such as the aforementioned Vicon Motion System for 3D motion tracking and the CODA Motion System (Mitchelson) for gait analysis can be used to produce the required motion trajectories. However, a typical setup for these motion systems involves prohibitively high costs per cubic meter of measurement space. Thus conducting research that involves motion analysis is typically restricted to high-end facilities or to projects with large funding. Instead of high-end tracking methods, low cost visual techniques such as blob counting are used to track participants in accessibility studies (Isard & MacCormick, 2001). Here however, information such as the participant's orientation is not available and only a few participants can be tracked using such a technique.

In this paper, we introduce an alternate tracking system called MoRe-T2 (Mobility Research Tracking Toolkit) that allows many unique trajectories to be easy tracked and characterised. A minimum working MoRe-T2 system only needs a computer, a paper printed marker and a video camera (e.g. a webcam). Thus, MoRe-T2 is low-cost and portable unlike the Vicon and CODA motion tracking systems. MoRe-T2 uses video cameras such as a webcam to track the pose of QR-code-like markers. The markers have two features of interest, which are that they enable orientation as an extra level of tracking information and they uniquely identify many participants. Both of these features of a marker are unavailable in markers of more standard techniques for video tracking like 'blob' detection (i.e. simply tracking a blob of a certain colour for example). Up to 4096 unique markers can be printed on paper, and then attached onto the bodies of participants or assistive technologies (e.g. wheelchair and scooter) to allows motion of these bodies to be tracked.

To use MoRe-T2, first we mount the cameras so that markers are visible to at least one camera at any point in time. The positions of the cameras are then estimated in a simple process that is performed once whenever the cameras are moved. Time synchronized videos of the motion of interest are then recorded. Recorded videos of a motion scene and the cameras' estimated positions are processed using a software called ARToolkitPlus library (Daniel Wagner, 2007). This software detects marker images in the videos and produces useful position and orientation information of the markers.

However, ARToolkitPlus has some limitations. It is not capable of generating trajectories from multiple cameras using the same inertial frame of reference. Also, it was originally developed for a VGA (640x480 pixels) resolution. For MoRe-T2, we developed software to combine the trajectories from several cameras into the same inertial frame. This software allows us to capture a continuous trajectory for a specific motion by stitching trajectories generated from all the cameras involved. In addition, we extended ARToolkitPlus working resolution to 3-megapixel (2048x1536 pixels). ARToolkitPlus produces poses that are inherently noisy, depending on the lighting condition, distance to the camera and quality of camera. We validated tracking performance at 3-

megapixel working resolution taking these dependency issues into consideration. In future work, we aim to employ a filtering technique to correct for temporary marker occlusions (Karavasilis, Nikou, & Likas, 2010). The system has been tested to work on Macintosh 10.9 and Linux Ubuntu 12.04.

The following section gives a high level guideline into MoRe-T2's setup procedure. Followed by this section is a validation of MoRe-T2's performance and characteristics such as accuracy, compared against those of the CODA Motion system. We then provide a specific case study of using MoRe-T2 to track a wheelchair motion.

Method

This section details steps taken to setup and produce trajectory results with MoRe-T2. These steps include guiding principles in selecting suitable cameras and correcting some common issues with the camera. For a minimum system setup, MoRe-T2 only requires the below hardware:

- One camera: For recording motion.
- One computer: For data processing and system control.

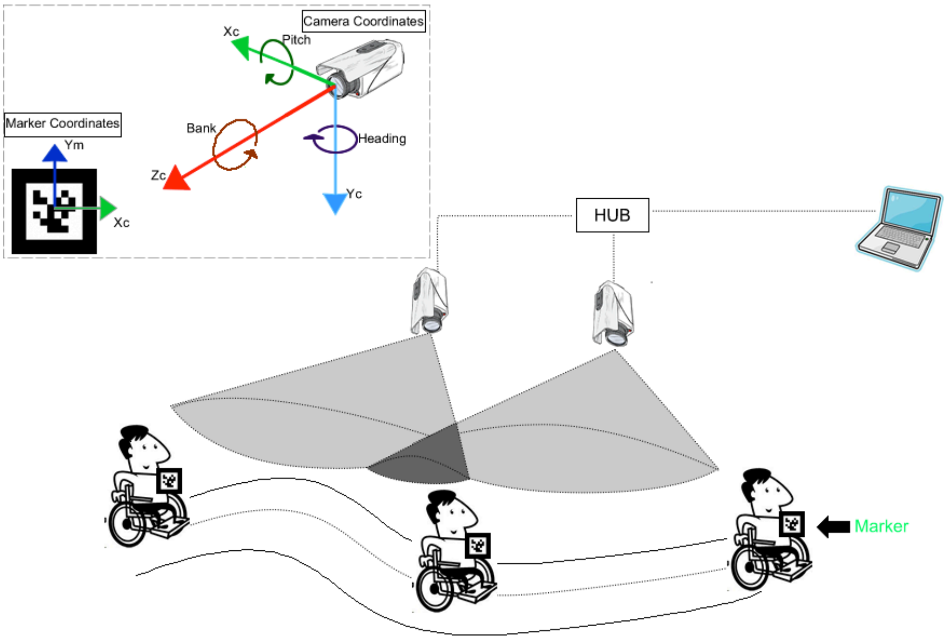


Figure 1. A camera and marker axis, and the general setup for the MoRe-T2 system.

To use the tracking system, the cameras are mounted at fixed positions from whence markers can be observed as shown in Figure 1. The markers are attached to the moving participant(s) or assistive device, and a video of the motion is recorded and then processed by the computer. To synchronize video recordings from more than one camera, MoRe-T2 captures the time all cameras began recording and removes any differences in these times. Other timestamps at any point in the recording can be captured as well to represent the beginning of an event such as a pedestrian walk or even data acquisition from other devices like an inertial sensor.

Before using MoRe-T2, the following one-time preliminary procedures are carried out in the order listed:

Camera Selection

A camera is selected based on its characteristics, which can be separated into connectivity, optics, and software compatibility (see Appendix A). Taking optics for instance, shorter exposure time may be preferable to reduce blur in motion capture (Raskar, Agrawal, & Tumblin, 2006). Selecting a camera may require making trade offs especially between cost and quality. One very important measure of quality is the maximum distance a camera can be used with MoRe-T2 to track markers. We can employ a mathematical rule of thumb (Peterson, 2009) that gives the maximum distance from a camera for a combination of camera characteristics and marker size as done in the case study subsection. This is very useful to ensure that camera selected is capable of working at intended distances. The rule of thumb is given:

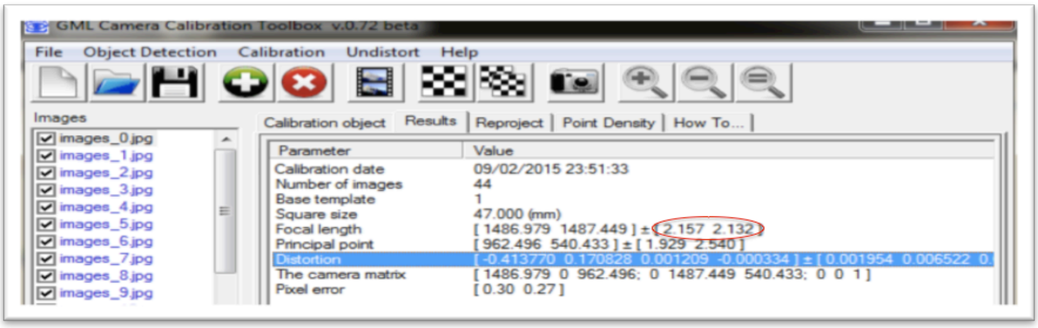
$$Distance_{max} = \frac{Focal\ Length * Camera\ Resolution * Marker\ Width}{sensor_{size} * 25} \qquad (1)$$

Where,

- Distance is the maximum tracking distance in mm.
- Camera resolution should be the minimum side measurement of the camera sensor’s resolution in pixels, different from the lens resolution.
- Sensor size is the camera’s sensor size.
- The number 25 represents the minimum detectable resolution of a marker in pixels (Kohler, Pagani, & Stricker, 2011).
- Marker width, focal length, sensor size and distance are all in mm.

Camera Distortion Correction/Calibration

To generate accurate trajectory results, MoRe-T2 requires that a camera’s inevitable curvature and/or distortion in its lens be compensated for. Several images of a checkerboard pattern of known size are taken from several angles and positions using the camera. A calibration programme, in this case GML C++ Calibration Toolkit (Vezhnevets, Velizhev, Chetverikov, & Yakubenko, 2005), can then use these images to calculate correction parameters, which are used by MoRe-T2 to ensure accuracy of the tracking system. This toolkit outputs an estimate of the camera’s focal length, principal axis and distortion parameters, along with a measure of uncertainty in these values as shown in Figure 2. The camera lens distortion is best compensated for when the uncertainty in focal length and principal point values is low, i.e. less than 4. Through testing, we found 4 to be a suitable upperbound in uncertainty. In Figure 2, uncertainty in focal length is circled in red and both of its values are below 4 pixels. Recommendations for taking calibration photos exist that ensure better camera calibration.



Parameter	Value
Calibration date	09/02/2015 23:51:33
Number of images	44
Base template	1
Square size	47.000 (mm)
Focal length	[1486.979 1487.449] ± [2.157 2.132]
Principal point	[962.496 540.433] ± [1.929 2.540]
Distortion	[-0.413770 0.170828 0.001209 -0.000334] ± [0.001954 0.006522 0.
The camera matrix	[1486.979 0 962.496; 0 1487.449 540.433; 0 0 1]
Pixel error	[0.30 0.27]

Figure 2. A typical camera calibration result

Camera Adjustment
For accurate tracking, all cameras are placed so that their fields of view are all approximately parallel to the major plane of motion. The major plane can for example be a ground surface across which a pedestrian's walking trajectory is recorded. To position the camera as intended, we place a marker flat on the major plane and adjust the orientation of the camera until that both the camera's attitude and heading angles are close to zero (or 360 degrees) as in Figure 3. MoRe-T2's GUI can show the pose of the camera with respect to the marker to guide the adjustment process.

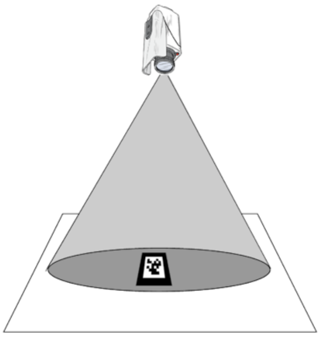


Figure 3. Camera is parallel to the plane of motion

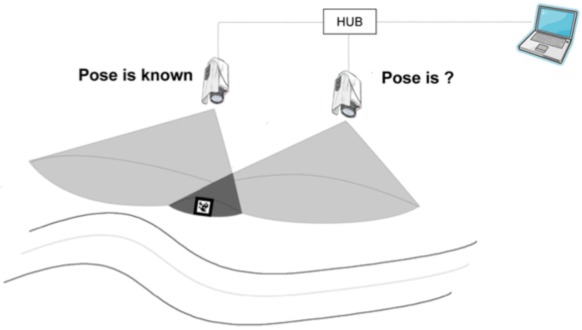


Figure 4. Unknown pose of a camera is estimate from a camera with known pose using a marker that is placed in an area visible to both cameras.

Camera Pose Estimation
After adjusting all cameras, we estimate their pose in an inertial frame of our choosing. We can represent the inertial frame's coordinate system using the pose of a specific camera or marker. That camera's pose or marker's pose will then be at the origin of the inertial frame. If we want a marker to describe the inertial frame, we simply place the marker as desired, noting from Figure 1, the marker's axis directions. Otherwise, we can pick a camera to describe the inertial frame. With any choice of inertial frame, obtaining the pose of other cameras from cameras with known pose can be necessary. The first camera with a known pose can be any camera that is visible to the marker at the origin or it can be the camera at the origin. To proceed with the estimation, we place a marker on the platform at a region that overlaps between the first camera with a known pose and another camera with an unknown pose. The GUI can then be used to estimate the pose of latter camera from the former. In this estimation process, unknown pose of a camera is transformed to the coordinate of the marker and then to the coordinate of the inertial frame, within which the camera with known pose resides. This process estimation is then repeated till all the cameras' poses are known.

Implementations and Results

CODA outperforms MoRe-T2 for most performance criteria such as accuracy but we were able to show that by trading off some high performance for low cost and portability, MoRe-T2 can generate valid and useful results. In this section, MoRe-T2's performance is validated and compared with CODA's performance.

Afterwards, MoRe-T2 is used to measure the trajectory of the wheelchair using four Internet protocol (IP) cameras.

MoRe-T2 Characteristics and Comparison with a CODA System

Portability, accuracy, maximum sampling time, occlusion of marker and ease of use are important characteristics that can be used to access the performance of a tracking system. For MoRe-T2, these characteristics are very much dependent on the choice of camera and the calibration quality of the camera. The ways in which using the system changes More-T2's performance is discussed in this subsection. In addition, we compare this performance with that of the CODA system.

Portability: MoRe-T2 is more portable than CODA. MoRe-T2 allows the freedom to select any camera that is either a USB camera or an IP camera. With this freedom, a user can choose cameras that have a small form factor. In addition, any computer system that is compatible with the cameras can be used for tracking and this computer can be detached once tracking is completed. On the other hand, each CODA tracking unit is several times larger than a USB or IP camera. This means that unlike MoRe-T2, CODA cannot be easy carried around.

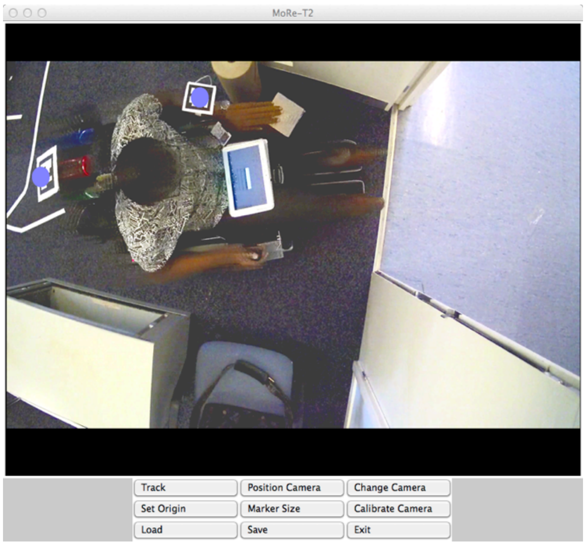


Figure 5. MoRe-T2 Graphical User Interface showing a two blue circles indicating markers were detected on a moving wheelchair and user.

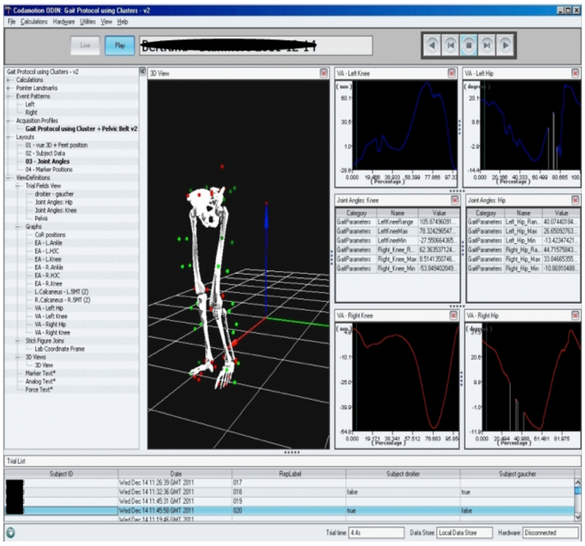


Figure 6. CODA motion user interface, which is more sophisticated and more complex than the MoRe-T2

Accuracy: This measures how consistently close the measured pose (position and orientation) is from the real world pose. The better the calibration of the camera, the better the accuracy. Lighting conditions also affect the accuracy. A typical well-lit environment, without the paper marker being overexposed to light is ideal. However, MoRe-T2 is more robust to a marker's exposure to dim light than to bright light.

Camera resolution and a marker's absolute size in pixel also play a role in accuracy. In general, the higher the resolution of the camera is, or the larger the size of the marker is, the higher the measurement's accuracy. A marker's absolute size can be increased by either making the marker bigger or bringing it closer to the detecting camera. The CODA on the other hand is more accurate with peak error less than two millimetres.

Sampling time: Sampling time depends on the frame rate of cameras used and the system's bandwidth, which is a measure of the capacity to acquire data from a camera. For either an IP or a USB camera, the sampling limit is the camera's frame rate typically around 30 frames-per-second (fps). The limit on CODA's sampling rate is 800fps, which is much higher than that of MoRe-T2.

Marker Occlusion and Artefacts: All motion-tracking systems track some form of marker. The paper markers of MoRe-T2 are larger than the markers of the CODA. This means that a MoRe-T2 marker may exhibit more motion artefacts as its surface area experiences more drag force by air current. Moreover, there is a greater chance of placing a larger marker around moving body parts that can impact on the marker. In general, MoRe-T2 markers are suitable for low-speed applications whereas the CODA markers are suitable for high-speed applications because of their small size.

Ease of use: Both MoRe-T2 and CODA are similarly easy to use when actually tracking. Setting up both systems follow similar steps: Position the camera units, mount the markers and define the origin of measure. However, extra steps are taken for MoRe-T2: create markers from paper, calibrate camera(s) and ensure suitable lighting. Considering user interface, the CODA has more functionality and thus a more sophisticated and complex user interface as shown in Figure 6. On the other hand, MoRe-T2 presents a simple interface and functionality for easy motion capture as in Figure 5.

Validation using the CODA

We validate MoRe-T2 by comparing its accuracy with the well-reported accuracy of CODA. We achieved a maximum peak-to-peak error of 77mm for MoRe-T2. This error value is greater than that of CODA, which is about 1.5mm as given by the manufacturers ("CODA | Human motion", 2005). To obtain the accuracy results for MoRe-T2, we attached a MoRe-T2 marker to a CODA marker and moved the pair of markers by some distance in a straight line along the x-y plane whilst recording absolute displacement from the start position. This procedure allowed us to track in real-time any discrepancy in accuracy between the MoRe-T2 and the CODA. Following from Pythagoras theorem, we used the error in the magnitude of displacement, $Error_{absolute}$ as the lower bound on both the error in the x-axis, $Error_x$ or the error in the y-axis, $Error_y$. The movement in the z-axis was more or less kept constant. Our error bound can be represented mathematically as below:

$$Error_x = X_{actual} - X_{measured} \tag{2}$$

$$Error_x, Error_y \leq Error_{absolute} = \sqrt{Error_x^2 + Error_y^2} \tag{3}$$

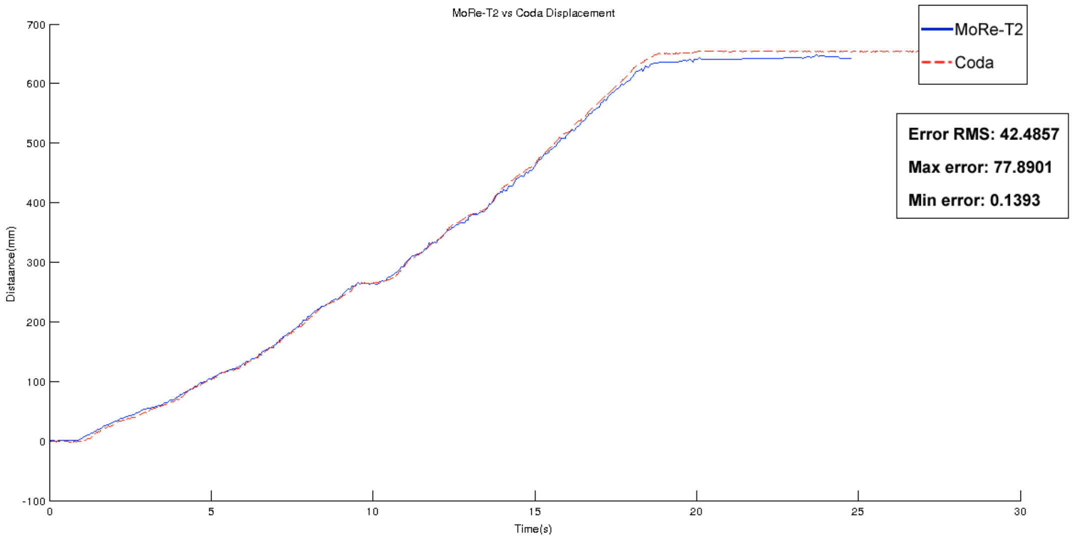


Figure 7. An example of tracked displacement of a MoRe-T2 marker fixed with a CODA marker. We can see a discrepancy between the measurement of MoRe-T2 and that of Coda, which is taken as our ground truth. The maximum error recorded was 77mm while the maximum RMS error for a single movement was 42mm.

The result of our validation is shown in Figure 7 where we obtained a peak error of 77mm and a root mean squared (RMS) error of 42mm. Although measurements are inherently dependent upon choice of camera and calibration, we obtained our result placing the marker of size 170cmx170cm at 5m from the 3-megapixel camera. Our lens distortion calibration output gave parameters with accuracy less than 3 pixels.

Case Study: Wheelchair Motion Tracking

This section gives a case study of using MoRe-T2 in transportation and accessibility studies. In this case study, we were interested in obtaining the trajectory of a wheelchair moving in a room. The room lighting was at natural daylight level. Four cameras were fixed to the ceiling in a U-shape overlooking the intended path of motion and the cameras’ field of view overlapped as shown in Figure 8. Each camera viewed an area of 3mx2m. Our maximum measurement distance from the camera was 3m and our marker size was fixed at 110mmx110mm. The marker’s size was constrained by the maximum distance of tracking and the available area upon which the marker was mounted. The maximum distance of tracking can be constrained by a camera’s viewing area size. These constraints were not strict but they were a useful upper bound in requirements guiding the camera selection process.

Figure 8**.** Four cameras connected in a U-shape.

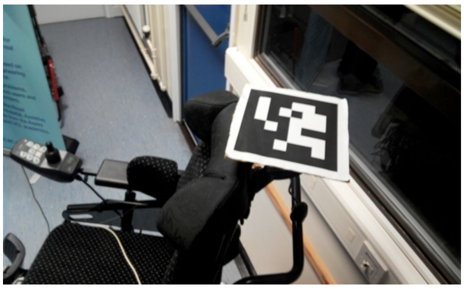


Figure 9**.** A marker attached to the top of a wheelchair to track the wheelchairs motion.

We chose to use IP cameras for their flexible setup capability and scalability. USB cameras on the other hand can complicate MoRe-T2 setup because they require repeaters to connect cameras at long distances. After choosing to use IP cameras, we generated a list of possible low cost IP cameras using the rule of thumb in equation (1) to determine a camera's maximum tracking distance (see Appendix B).

From Appendix B, Samsung 600 TVL was the cheapest that fitted our requirement. However, its long exposure time of 1/50s would have produced blurs in moving images (Raskar et al., 2006). We thus selected the next cheapest option the TRENDnet TV IP310PI, which had an exposure time going down to 1/10000s. Next the preliminary setup procedure was carried out. A paper printed QR code-like pattern was glued to cardboard to form a solid flat marker. This marker was then attached to a point on the wheelchair as shown in Figure 9. For origin and axis of the inertial frame, we selected a camera's pose. Alternatively, we could have used another marker's pose to describe our inertial frame. Lastly before tracking, the graphical user interface was used to confirm that markers are detected along the intended path. The graphical user interface displays the view of a selected camera and if a marker is detected in the camera's view, MoRe-T2 draws a blue circle over the marker indicating that the marker was indeed detected as shown in Figure 5.

Result

Figure 10 (a) and (b) both show the U-shaped motion of the wheelchair. From each camera, a unique colour code describes the marker's axis allowing us to differentiate trajectories generated by different cameras. Poses from different cameras overlap nicely and we show 6 of these at the 3 unique regions where the views of the four cameras overlap. The maximum overlap error is 80mm in the x and y camera axis and about 200mm in the camera z-direction.

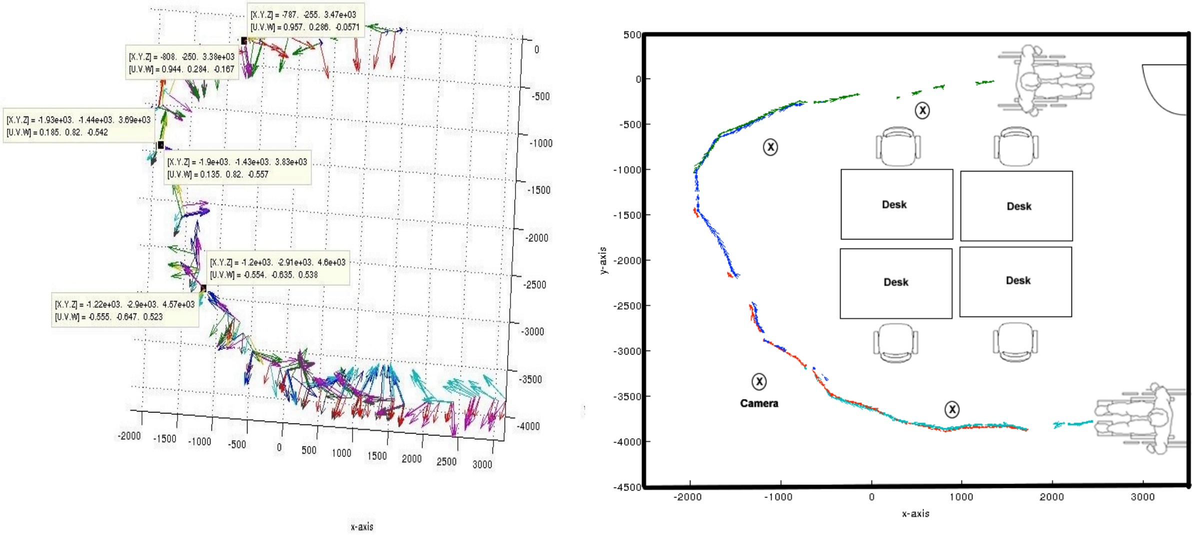


Figure 10 (A). Trajectory Graph Plot Figure 10 (B). Trajectory Plan view

Figure 10. The top view of wheelchair trajectory. Each camera's field of view overlaps with those of its nearest cameras. There are three regions of overlap and for each overlap region, the figure shows two poses of a single marker produced by the overlapping cameras at about the sametime.

Conclusion

We have presented and validated a low cost modular and portable tracking toolkit called Mobile Research Tracking Toolkit (MoRe-T2) based on the ARToolkitPlus library. For tracking performance, MoRe-T2 was able to achieve a worst-case peak error of 77mm and an RMS error of 42mm. Findings on MoRe-T2's accuracy showed better performance for closer distances to the camera, higher camera resolution and dimmer rather than brighter lighting. However, performance was also heavily dependent on calibration, lighting condition and marker's absolute size in pixel.

Further Work

We are currently looking to integrate the probabilistic effects of uncertainty to due factors such as camera sensor noise, lighting condition and occlusion. To do this, we can employ a Kalman or particle filter to enable an even more robust tracking performance.

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Appendix

Appendix A
Table 1 shows several criteria used to select a suitable camera for MoRe-T2

Category	**Quality**	**Details**
Connectivity	Data interface	USB cameras are limited to the number of USB ports available on the computer. Alternatively, a USB Hub can be used but the number of cameras is then limited by bandwidth of the USB port on the computer. More than 8 IP cameras can be connected to a single computer making IP cameras suitable for tracking in larger areas. Power over Ethernet (PoE) is especially attractive for IP cameras as it reduces the number of wires needed, encouraging a more flexible and longer distance setup. IP cameras have data cables that are typically much longer than USB unless repeaters are used for USB connection.
Optics	Focal Length	A longer focal length means a higher depth region within which an image is in focus. However, the field of view becomes narrower (Soldan, 2012).
	Lens exposure time	The smaller the exposure time, the less blurred a moving image will be (Raskar et al., 2006). However, images become darker which MoRe-T2 can tolerate.
	Sensor resolution	The higher the resolution of the sensor, the greater the distance from whence markers can be tracked.
	Sensor type	CMOS camera sensor can either be progressive scan, global shutter or rolling scan. Only rolling scan is not ideal since it requires lines of sensors acquiring image data are different times. This means that one picture of a moving image might appear malformed (Chia-Kai, Li-Wen, & Chen, 2008).
Software Compliance	Compression type	H264 and/or MJPEG compatible devices are most ideal for encoding objects in motion (Tourapis & Tourapis, 2003).
	Software Driver	USB camera need to have drivers compatible with the operating system should be used. For IP cameras, most only need a compatible browser to change settings.

Appendix B

Table 2 displays several example candidate IP cameras that may be selected for an experiment requiring a minimum measurement distance of 3m and a maximum marker size of 110mm x110mm

Camera	Sensor size	Sensor Type	Focal Length (mm)	Resolution	Shutter speed	Streaming	Max distance for 110mm marker	Price w/ vat
TRENDnet TV IP310PI Outdoor 3 MP PoE Day/Night Network Camera - network CCTV camera	1/3″	N/A	4	2048 x 1536	1/100,000	Yes	3.1928	£149.99
D-Link DCS 7010L HD Mini Bullet Outdoor Network Camera - network camera	¼″	Progressive scanning	4.3	1280 x 720	Variable (up to 1/2000)	Yes	3.7220	£199.19
D-Link DCS 7000L Wireless AC Day/Night HD Mini Bullet Cloud Camera - network CCTV camera	¼″	Progressive scanning	2.4	1280 x 720	Variable (up to 1/2000)		2.0774	£137.99
Link DCS-3710 HD WDR PoE Day/Night IP Camera	1/3″	Progressive scanning	12 mm	1280 x 960	Variable (up to 1/2000)	Yes	5.9866	£226.79
TRENDnet TV IP302PI Outdoor Megapixel PoE Day/Night Internet	¼″	N/A	4.2	1280 x 720	Variable (up to 1/2000)		2.0954	£176.39

Camera - network camera								
TRENDnet TV IP522P ProView MegaPixel PoE Internet Camera - network CCTV camera	¼”	N/A	4	1280 x 960	Variable (up to 1/2000)	Yes	1.9955	£129.59
Samsung 600 TVL 2.8-10mm varifocal lens IP66 bullet camera	1/3”	N/A	10	752 x 582	1/50	No	3.0243	£129.59

Appendix C

Although metrics are inherently dependent upon choice of camera and calibration, the table below is a typical value we obtained evaluated at 3m and 5m from a camera for a marker size of 170x170cm using a 3MP camera. Our lens distortion calibration output gave parameters with accuracy less than 3 pixels.

Table 3 showing the comparison of performance characteristics of MoRe-T2 and CODA motion system

Characteristic	**MoRe-T2**	**CODA**
Resolution		
Standard deviation of position static marker	At 3m 0.1822 in X axis 0.0927 in Y axis 2.8538 in Z axis 0.310 in Attitude 0.184 in Heading 0.074 in Bank At 5m 0.5911 in X axis 0.2094 in Y axis 8.9809 in Z axis 3.90283 in Attitude 5.2774 in Heading 0.2513 in Bank	0.05mm in X and Z axes 0.03mm in Y axis
Accuracy		
Peak to peak deviations from actual positions	±12mm in X and Y axis, when stationary ±39mm in X and Y axis, when moving ±38mm in Z-axis when stationary	± 1.5mm in X and Z axes ± 2.5mm in Y axis
Sampling rates:	Camera and interface setup dependent. Typically < 30Hz	56 sensors - 100Hz 28 sensors - 200Hz 12 sensors - 400Hz 6 sensors - 800Hz
Marker Occlusion	Greater likelihood because of larger marker size	Lower likelihood due to small form size
Motion Artefacts	Larger surface area incurs more drag force. Use for low speed applications.	Depends on how sturdy the marker is attached. Can be used for high-speed applications.
Ease of use	User interface is simple and camera position calibration is easier to perform	User interface is more complex and camera position calibration is more demanding to perform