Comparison of Tracking Methods for Augmented Reality-Supported Damage Mapping of Grid Shell Structures

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Abstract: As powerful mobile devices become available and robust tracking methods are further developed, Augmented Reality (AR) becomes increasingly suitable for use on construction sites. For the renovation of the Mannheim *Multihalle*, the world's largest free-form timber grid shell structure, various AR tracking methods are examined for their suitability for carrying out damage mapping: manual initialization (four points or vector input) and localization by cloud anchors. As the uniform grid of the grid shell makes orientation difficult during manual damage mapping, using a smartphone AR application to correctly recognize the laths and nodes is promising. Three key test criteria were used to compare the methods: the correct assignment of the laths, the smallest computationally recognized error and sufficient stability, meaning the absence of drift. In addition, the effort required for preparation and handling during use was considered. For the use case of damage mapping using a smartphone, the tests showed that although manual initialization using vector input is the most suitable method, even this method is not satisfactory. Therefore, in the outlook, measures to facilitate optical tracking and the use of differential GPS and synchronization with point cloud data are discussed.

Keywords: Augmented Reality (AR), Damage Mapping, Tracking, SLAM Systems, Cloud Anchors

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1 Introduction

During damage mapping of buildings, damages are recorded manually or digitally in order to plan structural changes to the building and to upgrade the structure based on the structural assessment. Augmented Reality offers the possibility of overlaying the real building with a virtual model of the structure during the survey. The *Multihalle* in Mannheim (see Figure 1) is the world's largest free-form timber grid shell designed by Pritzker Prize winner Frei Otto for Germany's National Garden Show of 1975. The experimental structure is considered an outstanding example of lightweight architecture and was classified as a cultural monument of special significance. The laths of the grid shell form a regular grid with a mesh size of 50 cm. As part of the upcoming renovation of the *Multihalle*, damages need to be repaired and the structure reinforced [1]. As it is difficult to orientate in the uniform grid of the lattice shell, mapping the damage is to be supported by overlaying it with a wireframe model in AR. The aim of digitally capturing the damages on a smartphone or tablet is to improve collaboration between planners and contractors and to make mapping more efficient by eliminating intermediate steps of sketching damage onto 2D paper drawings.

The tracking method is crucial for the correct superimposition of reality and virtual objects. For this purpose, various methods were tested on-site under field conditions. Based on on-site conditions and the constraints of the renovation concept, criteria for selecting the tracking methods were established for the use case and a pre-selection was made. In preliminary field tests, various optical methods were tested with "Simultaneous Localization and Mapping" (SLAM) systems for which sufficient visual features could be detected on the timber structure. Two manual initialization methods and localization via cloud anchors were selected for implementation in a demonstration application.

Figure 1: Entrance area of the *Multihalle* in Mannheim (Source: Fast + Epp).

2 Related Work

Previous approaches to AR in the construction industry can be found primarily in the visualization of planning. In other use cases, such as construction, operations and maintenance, development is mainly at the initial trial stage [2]. At the Technical University of Vienna, several approaches to AR are being pursued in which Building Information Modeling (BIM) is seen as a driving factor in advancing digitalization in the construction industry. Schranz et al. [3] summarized various possible applications, including applications in construction work and documentation, to support consultations, as well as for maintenance work and training. Gerger et al. [4] and Schranz et al. [5] describe possible use cases during the approval process in more detail.

Changing light conditions, large monochrome surfaces, repetitive patterns and moving objects pose particular challenges for tracking on construction sites. Urban et al. [6] analyzed commercially available AR systems with regard to their suitability for use on construction sites. They tested tracking with an infrared depth sensor at different lighting levels and investigated the influence of room size and the number of features in optical tracking.

Initialization is necessary for SLAM systems unless a previously recorded map can be used. Gehring and Mosler [7] as well as Marino et al. [8] used QR codes for initial tracking, with additional markers to reduce drift. Schranz et al. [9] identified four possible initialization methods. A comparison with QR codes proved to be the most error-prone. In the second option, in the course of a vector input, a point and a direction vector are marked by the user. The third option is to mark three orthogonal planes, which are taken from a BIM model. The authors have not yet tested the fourth option of carrying out the localization freely in the environment without markers. The previous investigations were mainly limited to use in solid construction. In this paper, the initialization methods are further developed with the aim of using them in the wooden grid shell of the *Multihalle*.

3 Method

To correctly superimpose reality and virtual objects, a total of six degrees of freedom (translation in three directions and rotation around three axes) must be determined by tracking. Not all methods can be used to determine all degrees of freedom. In addition, the tracking methods vary in their accuracy. As AR systems are mobile applications, they generally rely on the sensors built into the devices. Equipping the environment with additional sensors is not practical, especially in large environments.

3.1 Boundary conditions for tracking

To find the appropriate tracking method, the boundary conditions of the use case were considered. Initially, the local conditions of the grid shell were taken into account.

- Lighting conditions: The translucent membrane results in a predominantly uniform, diffuse light on the inside of the hall. Artificial lighting is necessary in the darker months of the year.
- Weather conditions: The hall has an open-sided roof. Fluctuations in temperature, air pressure and humidity are to be expected. Cold temperatures reduce battery life.
- Surface structure: The wooden laths provide a structured surface. However, the pattern is repetitive.
- Installation of markers: Possible in principle, but these may have to be repositioned after replacing individual building components.
- Structural changes, occlusions: Birdcage scaffold will be erected during the renovation.

Further constraints result from the functional requirements of the software application for damage mapping. The accuracy of the tracking is key for being able to assign damages to individual building components such as laths and nodes. The deviation should be less than half the mesh size of the grid, ideally no more than 15 cm. Simple handling is important for the continuous use and acceptance of digital damage mapping on the construction site. The application was implemented using the Unity Game Engine and license-free software development kits (SDKs). For the on-site tests, an Android smartphone was used.

3.2 Preselection of tracking methods and preliminary investigations

Based on the described boundary conditions, a preselection of potentially suitable tracking methods was made (see Figure 2). In preliminary investigations, scanning a single marker proved to be too inaccurate for localization, especially with regard to rotation. With the *AR Foundation* sample app [10], however, sufficient features could be recognized on-site for markerless tracking. However, geometric planes were recognized quite arbitrarily. The depth information of the LiDAR sensor was discarded due to the short range of the sensor in the test device. Although SLAM is generally suitable, tests with the SDKs from *Immersal* [11] and *Easy AR* [12], which use pre-recorded point clouds, did not provide sufficient accuracy. With the *Immersal* mapper, point clouds can be generated by taking overlapping photos. During tests on site, deviations of up to 70 cm could be observed, which is significantly more than one mesh size. With *Easy AR*, the point cloud recorded in an AR session can be saved on a server together with virtual objects created by the user. Virtual objects added in the tests were sometimes displayed at a different location later or jumped to a different location during display. Both SDKs do not offer any customization options to improve precision.

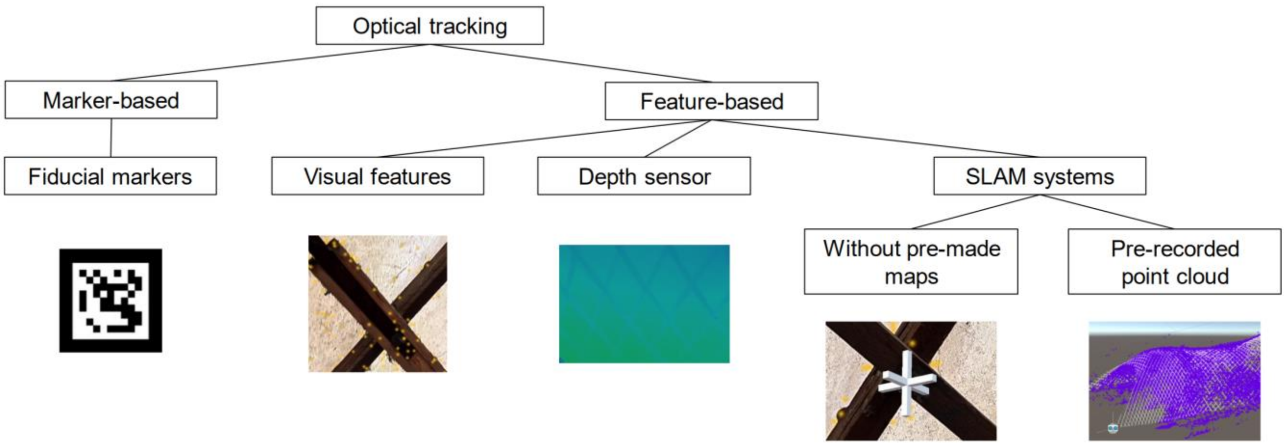

Figure 2: Overview of the tracking methods analyzed in preliminary tests.

3.3 Implemented tracking methods

During implementation, attention was paid to the adaptability of the methods to improve accuracy. The methods implemented in the demonstration application are shown in Figure 3.

- Manual initialization using four points: The user marks four points on the grid shell to determine the transformation between the world coordinate system and the local coordinate system of the AR application. Theoretically, the coordinates of three points would be sufficient to locate a model in space. However, as the points cannot be expected to match exactly, an approximate calculation is carried out for which at least four points are required.

- Manual initialization via vector input: The user only marks one point as the origin and one horizontal direction. As the smartphone's inertial sensors have already detected the orientation to the earth's surface, this information is sufficient.
- Localization via *Google* cloud anchors [13]: The cloud anchors are marked in advance. For hosting, the point cloud around the anchors is captured from all sides. An indicator shows the quality of the point cloud. When sufficient quality is achieved, the point cloud is transferred to the server. As it is difficult to correctly record the rotation of the cloud anchors on the grid shell, only the position of the cloud anchors is evaluated during tracking. As with manual initialization, at least four anchors are required. These must be evenly distributed and must not lie approximately on a line. For localization, the user walks along the walls of the grid shell until enough anchors have been found. It is also possible to continue the search for cloud anchors after the model has been localized and to update the position of the model later. The calculation used provides a computational error of the individual anchors. If the deviation of an anchor is too large, it is excluded from the calculation. Figure 4a shows the result of a successful superimposition.

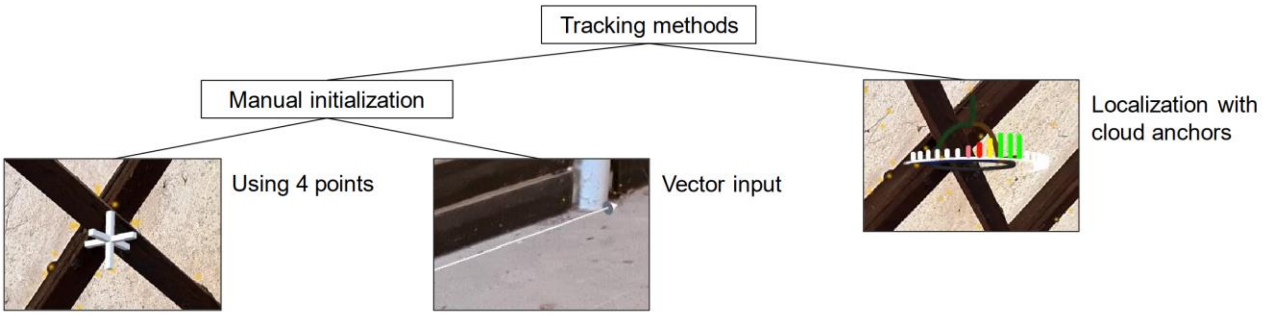

Figure 3: Tracking procedures implemented in the demonstration application for damage mapping.

After initializing the tracking, the user can select one or more components on the grid shell and enter a description of the damage using a menu (see Figure 4b). Additionally, it is possible to take photos for documentation purposes. Damage can be directly flagged for repair or marked for approval.

(a) Superimposition with 16 cloud anchors (outliers marked red). (b) Menu for mapping.

Figure 4: On-site use of the damage mapping application.

4 Experiments and Results

To evaluate the tracking methods, they were tested in a final on-site test under standardized boundary conditions. Three test criteria were defined for this test:

- Clear assignment of the individual lath sections
- Largest recognized computational error of an anchor point after positioning
- Time in which the superimposition remains stable until drift is detected

The tests were carried out over a maximum period of two minutes. For manual initialization, positioning using four points and vector input were tested. For localization via cloud anchors, variants with four anchors without updating and with eight and sixteen anchors with continuous updating were tested. Ten runs were carried out for each method. The results are summarized in Figure 5.

10 runs per method	Manual Initialization		Cloud Anchors		
	4 Points	Vector input	No updating	With continuous updating	
			4 anchors	8 anchors	16 anchors
Frequency of precise allocation	10% ●○○○○○○○○○	90% ●●●●●●●●●○	40% ●●●●○○○○○○	40% ●●●●○○○○○○	50% ●●●●●○○○○○
Average maximum alignment error	0,31 m	Not applicable	0,24 m*	0,24 m	0,47 m
Stable superimposition (measured in 10 second intervals over 2 minutes) 0% 50% 100%					

* Only runs with a maximum deviation of 1 m were taken into account

Figure 5: Results of the comparative test.

In the comparative test, manual initialization via vector input achieved the best results with a success rate of 90%. However, in only one third of the cases the superimposition remained stable for at least two minutes. After a loss of tracking, it was possible to resume tracking after returning to the initial location. When marking four nodes, drift already occurred during initialization. When using cloud anchors, some anchors were detected incorrectly. This influenced the alignment of the model so that only 40%–50% of the runs achieved sufficient accuracy for damage mapping. The overlay was less stable for the variants with continuous updating, which is due to the fact that localization can also become less accurate when adding additional anchors with a larger deviation during updating.

5 Discussion

Precision is the most important factor for damage mapping. Only if the components can be clearly assigned, it is possible to carry out the mapping reliably with the application. If laths are mixed up, this can lead to a repair being carried out in the wrong place. The vector input achieves an almost exact overlay. The precision of localization using cloud anchors is impaired by the fact that individual cloud anchors are recognized in the wrong position. The manual initialization using four points is not pursued further due to its low success rate. To ensure the usability and efficiency of the mapping, it is also important that the overlay remains stable for as long as possible. The SLAM systems used still need to be improved for this purpose.

Another criterion is the preparation effort. For manual initialization, only the coordinates of the points to be marked need to be stored in the application. These can be easily replaced in case of changes. For localization via cloud anchors, they first have to be captured. The accuracy and lighting conditions when hosting the anchors are essential for how reliably they can subsequently be resolved. Creating a sufficiently dense network of cloud anchors for the *Multihalle* would take around six working days. However, a new network would have to be created, if the local conditions change.

To compete with manual mapping, the application needs to be robust and user-friendly. In practice, the need to repeat the initialization when tracking is lost, could result in frustration outweighing the increase in efficiency through digital mapping. The advantage of using cloud anchors is that scanning takes place automatically in the background. Nevertheless, the precision and drift are still too high for a reliable application for damage mapping, making further optimization necessary.

6 Conclusion

For damage mapping in the *Multihalle*, a high degree of accuracy in the range of 15 cm–20 cm is required to ensure the correct recording of damages. A reliable, stable overlay and simple handling are required for practical use. The methods tested do not yet fulfil these requirements. However, the accuracy would be sufficient for other purposes such as indoor navigation or a digital tour.

To improve tracking, point clouds created from survey data could be analyzed further. Using point clouds created from terrestrial laser scanning data is expected to result in higher accuracy. By comparing point clouds across a large area, tracking could also be more stable in terms of occlusions, as only small areas would be covered at any given time.

Furthermore, positioning using cloud anchors could be optimized by means of a parameter study. The number of anchors to be used for localization could be limited and optimized depending on the distance between the anchors on the structure. Another option would be to use cloud anchors only in a certain radius around the position of the user.

As an alternative to optical methods, tracking using differential GPS could also be investigated. However, as this requires an unobstructed line of sight to several satellites, it is only suitable for outdoor use. The extent to which the quality of the signal is reduced even by light roofing, as in the *Multihalle*, to enable precise localization inside would have to be tested. However, this process would be feasible for the use on the exterior of the lattice shell.

The tests carried out show the need for further research into mobile tracking methods to open up further uses for AR in the construction industry with high precision requirements.

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