Beyond 3D "as-Built" Information using Mobile AR enhancing the Building Lifecycle Management

Svenja Kahn, Manuel Olbrich, Timo Engelke, Jens Keil, Patrick Riess, Sabine Webel, Holger Graf, Ulrich Bockholt
Fraunhofer IGD
Darmstadt, Germany
e-mail: {first.last}@igd.fraunhofer.de

Guillaume Picinbono
CSTB
Sophia Antipolis, France
e-mail: guillaume.picinbono@cstb.fr

Abstract— **The success of smartphone technologies changed the way information is processed as more and more geo-referenced structures are emerging linking information to specific locations within our environment. Thereby, Augmented Reality has become a key technology as it analyses the smartphone sensor data (camera, GPS, inertial) to derive the detailed pose of the smartphone, with the aim to correlate our real environment to the geo-referenced information space. In particular, this is relevant for application fields where 3D-models are used in planning and organization processes as e.g. facility management. In facility construction and management Building Information Model (BIM) was established as a standard that not only holds the 3D-building-geometry but encompasses pipe/electrical systems as well as semantic building information, for example properties and conditions of building components. With this motivation our work integrates BIM and Augmented Reality.**

Keywords-Mobile Augmented Reality, Building Lifecycle Management, Camera Tracking.

I. INTRODUCTION

Construction and Facility Management is a business area associated to large investments and high efforts for planning, preparation and maintenance. Here, several stakeholders with different interests and backgrounds like facility managers, architects, craftsmen etc. have to cooperate. Discrepancies in communication, documentation and planning cause high consequential losses. This is the reason that "Building Information Models" (BIM) have been established during the last years that are consolidating all relevant information related to building facilities. One major aim is to manage information related to the lifecycle of the building envelope. This implies the management of the overall lifecycle processes starting from its design and construction through its operation, maintenance, refurbishment stages, and finally in its destruction ensuring a feedback loop of learned best practice to future projects.

While several mature solutions do exist for earlier stages, there is still a lack of supportive management tools within later stages, i.e. during the operational and maintenance phase of the building. In particular the feedback of information in view of changes to the building envelope is only fractionally or not at all digitally supported. Paperwork is still a predominant working metaphor for documentation. With respect to this bottleneck, this paper shows how Augmented Reality could be used as supportive technology for documentation during operational and maintenance phases of the building lifecycle.

The presented work is structured as follows: Section II provides an overview of the state-of-the-art and Section III specifies the proposed lifecycle building integration concept (LifeBC) for fusing BIM data with mobile AR. Section IV addresses our mobile AR framework (which combines embedded tracking technologies on smartphone platforms with an AR server-client infrastructure). Section V details our HTML-based annotation engine for real-time content generation. The technological contributions presented in Section IV and Section V provide the basis for the use cases proposed in Section VI, where this paper illustrates use cases for supporting the documentation and maintenance of building related information with mobile AR applications. The paper ends with conclusions in Section VII.

II. STATE-OF-THE-ART

The increasing importance and availability of 3D models in the construction and facility management industry offers a future where 3D "as-built" information will not only be available during the construction phase, but also during the whole lifetime of a building. This trend is reinforced by the success of BIM that supports the process of generating and managing building data related during the building life cycle [9][12]. BIM encompasses building geometry and its spatial relationships as well as technical installations and building components, such as cables or heating systems. BIM data has proven its high potential for the reduction of costs resulting from inadequate interoperability in construction processes [24].

During the lifecycle of a building, the data contained in the Building Information Model needs to be complemented with a multitude of additional building related data such as instruction manuals for technical installations, lifecycle documentation, or maintenance plans. In current state-of-the-

art processes, this information is processed with facility management systems, e.g. Archibus [1], Nemetcheck [15] or SpeedikonFM [19]. Whereas these systems offer a wide range of functionality for storing and maintaining building related information within the software, the stored data is not easily accessible on-site and (apart from some RFID-based approaches) usually is not linked to real objects. This can cause cumbersome and tedious work flows, especially for large facilities such as industrial buildings, factories or trade fairs.

This work contributes to overcome these limitations by integrating BIM data with Augmented Reality on mobile devices. The processing power of mobile devices has steadily increased in the past years, resulting in the development of first mobile tracking approaches [2][14][21]. However, these approaches do not fulfill the BIM related requirements for AR applications, such as a good scalability for devices with different processing power and the possibility to fuse 3D building models with semantic annotations as well as tracking reference data. There are only very few previous works in which both AR and BIM have been addressed in the same context [11]. However, an overview of the usefulness of AR for the construction and building facility sectors in general was shown in several studies [8][22]. For instance, Shin and Dunston [18] pointed out that Augmented Reality can support work tasks such as inspection, coordination, interpretation and communication on construction sites. Augmented Reality supports labor effective methods by presenting construction information in a way which is easy to perceive.

III. CONCEPT

The aim of LifeBC lifecycle building integration concept is to integrate 6D indoor tracking technologies with "Evolutional Building Models" to support applications in the AEC (architecture, engineering and construction) domain. Therefore, we develop multisensory technologies for mobile computing systems that are capturing our real world and that are registering the 6D pose of the mobile device in real-time. Our infrastructure consists of several connecting mobile devices ("players solution") with a central backbone holding the building related information ("building cloud"). The information model we are using integrates all building related data and enhances the BIM with multiple user captured media data. Augmented Reality is used as front end for the visualization of BIM data, for annotation of requests, for lifecycle documentation and monitoring of building components throughout the deployment phase.

Focus of the presented solution is to establish a closer link to the underlying BIM and to integrate BIM information on mobile platforms using Augmented Reality with the aim:

- to offer an AR-tool for the documentation of maintenance and service procedures on recent smartphone systems
- to fuse 3D building models with semantic annotations as well as tracking reference data using standardized HTML5 interfaces
- to realize an AR-service based infrastructure that uses the smartphone for environment capturing and AR-visualization on the client while processing content and tracking reference models on the server
- to establish an HTML-based annotation engine that links BIM and multi-media content to building parts supporting real-time content authoring, and
- to downscale markerless/large-area tracking technologies to smartphone devices and Tablet-PCs.

The technology builds on open standards for a seamless integration of the developed technologies into established workflows. Using advanced capturing technologies a 3D feature map is learned continuously. This 3D feature map holds the 3D position of the features, as well as specific criteria that characterize the features and that allow an identification and classification of the 3D features. An online learning process continuously updates and enhances the 3D feature map used as reference data for the tracking. We integrate the captured 3D feature map with the BIM, granting access to the 3D model including relevant infrastructure elements like electrical wires or pipe systems. Thus, the BIM provides the 3D-model as starting point for the tracking reference data. Our three main contributions for supporting the documentation and maintenance of building related data with mobile AR applications are:

- A mobile AR framework which consistently builds on open standards and which accounts for different processing powers of mobile devices by combining embedded on-device camera tracking with a server-client approach for mobile devices whose processing power is not sufficient for estimating the camera pose directly on the mobile device (Section IV).
- An annotation engine which links spatially registered user annotations to the corresponding objects in the BIM model (Section V).
- Use cases which show how the integration of BIM with AR and the mobile AR framework in combination with the annotation engine can support building related documentation and maintenance tasks (Section VI).

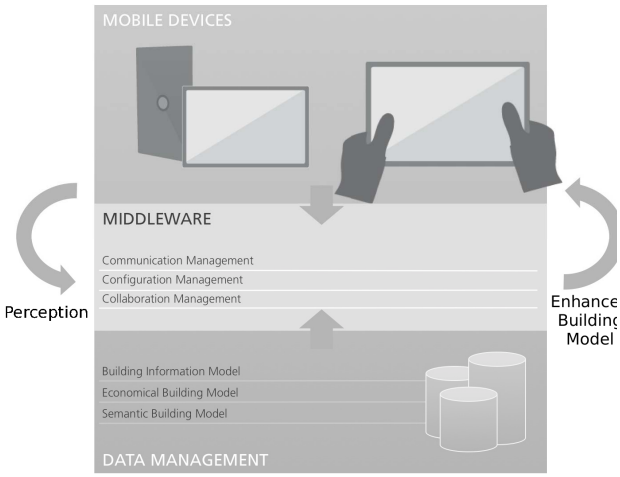

Figure 1. LifeBC Architecture.

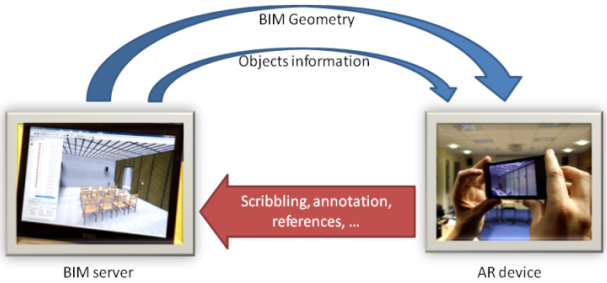

Figure 2. Data exchange between BIM database and AR device.

IV. Mobile Camera Tracking

In this section, we present a scalable mobile AR framework that provides the technological basis for supporting BIM with mobile AR applications and that accounts for the hardware capacities of different mobile devices:

- If adequate computational power of the mobile system is available, the 6D tracking is performed in real-time on the device itself (parallelizing tracking and 3D-reconstruction).
- If the mobile system is limited in computational power, the captured data is transmitted to the central backbone. The tracking is performed on the server. After processing, enhanced data including relevant information is retransmitted to the mobile system.

The proposed approach makes it possible to use all tracking methods on all devices, independent of the processing capabilities of the mobile devices. In our Augmented Reality framework InstantVision [3], the available markerless camera tracking technologies encompass (amongst others) point-based and edge-based camera tracking [25], model-based analysis-by-synthesis methods [26], the reconstruction and alignment of 3D feature maps [23] as well as visual-inertial structure from motion [5][6]. Furthermore the tracking and initialization methods comprise BAG of visual words [7][13] and HIPs [20]. With the approach described in this section, all these methods can be used on mobile phones as well.

A. Camera Tracking on Mobile Devices

This section describes the key concepts for supporting BIM data with mobile Augmented Reality applications on mobile devices which are powerful enough to calculate the camera pose directly on the mobile device itself. While other state-of-the-art approaches are based on device specific solutions, our approach consistently builds on open standards (HTML5, JavaScript and X3D) for a seamless and device-independent integration of all required components:

- AR applications are declared with HTML5 and JavaScript.
- Perspective 3D and 2D content is embedded with the ISO X3D standard.
- The user specifies the desired tracking algorithms with XML configuration files. The tracking algorithms are executed by a platform independent and scalable computer vision engine [3].
- Data scalability is ensured by the combination of a distributed database with local storage on the mobile device.

A major advantage of our mobile tracking framework based on open standards is the reusability of its components. For example, tracking algorithms can be replaced without the need to adapt the other parts of the application. Previous approaches such as PhoneGap [16] provided either only a small subset of rather simple functions or were limited to specific tracking technologies, for example marker based tracking [17]. Furthermore, in contrast to previous approaches, our mobile tracking framework is able to interface several multithreaded engines which are executed in background processes.

The main components of our mobile AR architecture are shown in Fig. 3. In order to unify the mentioned building blocks, we have created a uniform viewer for the mobile iOS and Android platforms. It utilizes an HTML5 and JavaScript (JS) based web component. Special JS interfaces allow to access and connect data of the render engine and the computer vision engine InstantVision [3]. Our framework layers a transparent Web-Kit implementation over an X3D render engine, which directly communicates with the computer vision engine. By specifying abstractions in form of JS interfaces, the developer is able to load, modify, replace, and remove parts of the descriptions and thus to dynamically generate applications. Callbacks can be configured with AJAX services. With these interfaces, it is possible to access real-time information about the current tracking status, to process and to exchange data between the JS-Engine and the other processors in the backend. The lightweight mobile X3D render engine can render a subset of the standardized X3D nodes. In order to display the camera image in the background of the scene for the AR applications, we have extended X3D by an additional "PolygonBackground" rendering node [10].

To ensure data scalability, we combine a distributed server-based database with a hierarchical local database on the mobile device. The server-based database is a CouchDB database [4]. The CouchDB database stores the building related information, the configuration of the AR Application and the tracking data. The tracking data covers for example reconstructed 3D feature maps and device specific calibration data, such as the intrinsic camera parameters. It is possible to transfer partial or full tracking data via a network

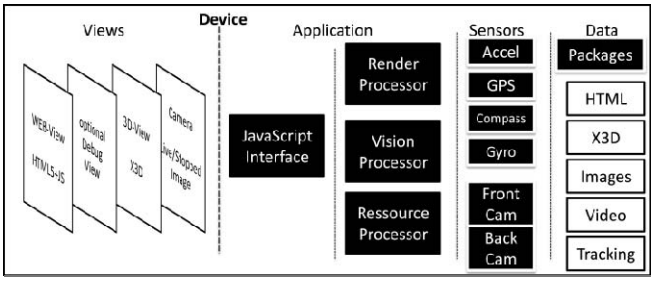

Figure 3. Our generic AR architecture for mobile devices. A JavaScript interface allows steering and connecting render-, vision-processor and other resources.

to and from a server infrastructure with XMLHttpRequests.

The camera pose is calculated directly on the mobile device by the platform independent computer vision framework InstantVision [3]. Table I shows the tracking frame rate (frames per second) for three different mobile devices. The image width and height is the size of the image used for the camera pose estimation. In the "sparse" mode of the Lucas-Kanade feature tracker (KLT), approximately 15-30 features of a reconstructed 3D feature map were tracked in each frame. In the "dense" KLT mode, at least 50 features were tracked in each frame.

The tracking accuracy is permanently observed by the system. If the accuracy of the vision based tracking is not sufficient (for example, if there are only few distinguishable features in the current camera image) or if the pose needs to be (re-)initialized, the pose is coarsely estimated from the built-in sensors (accelerometer, gyro or GPS if available).

TABLE I. TRACKING: FRAMES PER SECOND ON MOBILE DEVICES

Device	iPhone4		iPad2		Nexus-S	
Image Width	320	640	320	640	320	640
Image Height	240	480	240	480	240	480
Marker Tracker	30	18	30	19	30	17
Poster Tracker	19	14	30	30	17	10
KLT (sparse)	12	9	25	17	11	8
KLT (dense)	6	4	14	8	5	3

B. AR Client/Server Infrastructure

The client-server infrastructure is used to realize AR applications on mobile devices whose processors are not powerful enough to do all the necessary processing themselves. A typical example for which server-client based tracking is very useful is the realization of markerless Augmented Reality applications on smartphones. Despite the fact that individual processing power is steadily increasing, it is still notably smaller than the processing power of custom desktop computers.

The application layer of the AR client-server infrastructure is based on the Hypertext Transfer Protocol (HTTP). The Transmission Control Protocol (TCP) is used as transport layer to transfer data from the client to the server and vice versa. The carrier is a typical wireless network. Our infrastructure is set up in a way that the clients send HTTP requests to the server. These requests usually contain the currently captured camera image together with additional application related data. Afterwards, the received data is processed by an instance of the computer vision module on the server and the result is sent back to the client.

If the processing speed of the client is significantly lower than the processing speed of the server, a smooth AR application can nevertheless be ensured by minimizing the calculations on the client and by shifting most calculations to the server. In this case, only the image acquisition of the camera on the mobile device and the visualization of the augmented image is processed on the client. All other calculations (image processing, camera tracking and the calculations needed for the AR application) are processed on the server. This approach has the advantage that the feasible complexities of the image analysis, the camera tracking module and the application are only restricted by the processing capabilities of the server. This is advantageous for complex applications because the processing speed and the available memory of the server can be upgraded more easily than the processor, the working storage or the graphics card of the mobile device. Thus the entire range of markerless camera tracking approaches can be used for Augmented Reality applications on mobile devices as well, independent of the used processor. On a mobile Nexus-S device, this client-server approach runs with a framerate of 12 frames per second and with a latency of 180ms if the captured camera image has a resolution of 640x480 pixel and if the output (screen) resolution has a resolution of 800x480 pixel. The framerate is independent of the tracking method applied on the server. A further advantage of the proposed approach is that it is also possible to augment the image with augmentations which can not be rendered on the mobile phone itself, for example complex and large 3D models in arbitrary data formats.

V. ANNOTATION ENGINE

In this section, we describe the annotation engine for adding annotations to the BIM data. The main motivation for the annotation engine is to provide means to annotate BIM data directly on site, without the need to return to a workstation. With our mobile AR based annotation engine, content can be added to the system on site and on the fly. For example, technicians detecting an issue can directly record the problem where it occurred and do not need to return to a workstation to insert a description of the issue into the BIM system. Our annotation engine

- is based on open standards (X3D, HTML)
- can be used on arbitrary devices (mobile phones, desktop platforms or workstations)
- supports an AR mode for on-site annotations as well as a VR mode for annotations on workstations
- can either be used in single-client mode or in multi-client mode (synchronizing several distributed annotation clients)
- spatially registers annotations with the BIM 3D model, which directly links annotations with the correct corresponding object of the BIM 3D model.

The spatial registration of the annotations (which is based on the alignment of the 3D model with the real world via camera tracking and AR) makes the recorded annotations easily accessible later on. When a facility manager inspects a location, the AR system visualizes all the annotations, which were acquired at and linked to the corresponding part of the 3D model. Thus, the user does not need to search a textual database for previously gathered annotations. Instead, he can directly access them via their positions in the building.

A. Annotation Interface

The annotation interface is modeled with X3D. On session setup, the user can start or join a session and select a 3D model with previously generated annotations. The

Figure 5. User Interface in VR- (top) and AR-Mode (bottom)

Figure 4. Annotation engine on mobile device and on workstation.

annotation interface contains tools for navigating in the model, and for creating, displaying and modifying annotations. Each annotation stores the 3D position of the annotation in the physical building as well as a textual description, a set of attributes and attachments. All annotations are linked with the BIM data by their 3D position in the physical building and by the BIM object which is situated at this physical location. Fig. 4 shows the 3D positions of annotations represented by marker symbols. Each annotation marker provides a first small subset of the annotation information via its color and ID. Furthermore, it serves as a button to access the full annotation information. The top image in Fig. 4 shows an open annotation on the right side, which contains a textual description as well as an attached image. Taking a snapshot with the camera of the mobile device is a fast and easy way to document the current state of an object in a building. After taking a snapshot, the user can mark or highlight important image areas. When several annotation clients are connected, users can share viewpoints and annotations with the other clients. Mobile users can stream their position in real time to other users.

Fig. 5 visualizes the use of the distributed annotation engine on a mobile tablet PC and on a workstation. Whereas on the workstation the annotation system is a pure VR application, the annotation system on the mobile device uses the mobile AR framework described in section IV to link the pose of the mobile device in the physical building with the corresponding part of the virtual 3D model. In this mode, the camera pose of the real camera is tracked and sets the pose of the virtual camera. When the user moves the tablet PC, the real camera image is augmented with the virtual content. The bottom image in Fig. 4 shows the annotations augmented onto the image captured by the camera of the mobile device.

B. *System Architecture*

Fig. 6 visualizes the system architecture of the annotation engine. While it is possible to use only a single client, it is also possible to synchronize several annotation clients with a synchronization server. The first annotation client that initiates the session is used as a hub for data synchronization ("synchronization server"). Each client consists of three major components: a database, an information server and an X3D browser. The database locally stores the annotations. It is synchronized with the databases of the other clients. The information server is responsible for the session setup, for data storage, synchronization and for data representation. The X3D browser displays an X3D scene, that contains the 3D model (from the BIM data), the annotations and the user interface. In addition to the interfaces visualized in Fig. 6, the X3D browser is also connected to the mobile AR framework described in the previous section, which provides the position and orientation of the mobile device.

The communication between the X3D scene and the information server is HTTP based. A JavaScript node in the X3D scene uses an XMLHttpRequest object to access and to deliver information to the information server, whereas the server uses a REST interface to trigger actions in the X3D application. The information server provides the annotation data as an HTML site. Thereby, the annotations can be accessed with any web browser. They are integrated in the X3D scene with a BrowserTexture X3D extension node, which also gives the user the possibility to add data and to modify existing data. When the user clicks on the touch screen of the mobile device to add a new annotation, the system calculates the position of the annotation on the 3D model by intersecting the view ray through the clicked point with the 3D model of the building.

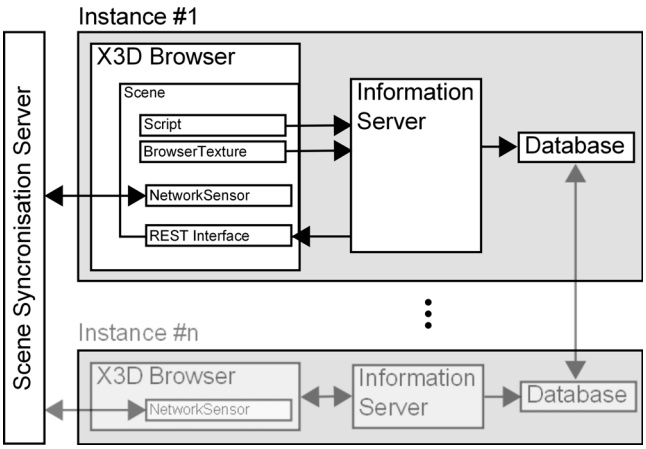

Figure 6. System architecture of the annotation engine.

VI. USE CASES

In this section, we propose use cases which show how the integration of BIM with AR and the mobile AR framework in combination with the annotation engine can support building related documentation and maintenance tasks.

Talking with experts, one of the major building related issues still is an integrated process chain from identifying damages during an inspection phase, followed by its documentation, up to finally solving the incidents. Current state-of-the-art processes apply facility management systems (e.g. [1], [15], [19]). While these systems offer a wide range of functionality for storing and maintaining building related information, the stored data is not easily accessible on-site. This causes cumbersome and tedious workflows, especially for large facilities. Envisioned changes or detected damages first need to be documented manually on site (for example on a sheet of paper). This information can only be added to the facility management system after the building manager has returned to a workstation, where he has to document the relevant information anew. The same accounts for information from the BIM database, which has to be printed on paper before it can be used on site.

Therefore, we first present a use case which illustrates how BIM based AR can support the different steps of a building related process chain. An integrated demonstrator for a similar process chain was realized for the CSTB premises in Sophia Antipolis, for which a detailed BIM model exists, which models the whole building. The CSTB BIM/AR demonstrator uses the server-client approach described in section IV.B for the AR based on-site analysis. The camera pose is estimated by tracking the 3D features of a reconstructed 3D feature map [23]. A mobile phone was used for the on-site analysis and a tablet PC for the annotations.

A. Use Case: Installation of a Ventilation System

Our first use case illustrates how BIM based AR can support the different steps required for the installation of a ventilation system. The exemplary application scenario of LifeBC for a ventilation system includes the technical planning, the technical installation and the documentation of the performed operations.

Step 1: Technical planning
For the reduction of energy, a new ventilation system should be installed in an existing office building. The engineer who is responsible for the planning of the technical installations in the company enters the technical room with his mobile computing system. With the smartphone integrated video camera he captures the room. Using the annotation tool he can scribble in an overlay to the captured pictures where the main components of the service installation should be placed. After finishing the annotations, the room planer connects to the LifeBC backbone. He transmits his planning data to the enhanced BIM. His planning data is included into the BIM related database and is geo-referenced within the 3D-model of the building.
Step 2: Technical organization
The BIM is accessible via the LifeBC workstation (Multi-Touch PC). Here the building manager reviews the technical planning; he distributes the tasks resulting from the technical planning to different craftsmen that can solve the task. The craftsman responsible for a specific task receives his tasks including all related information of the BIM as an action assignment on his mobile computing system and enters the relevant part of the building. In an augmented reality set-up he receives the planning data as superimposition to his captured camera pictures.
Step 3: Technical installation
Before installing the ventilation system, the technician has to control if the available pipes and electrical cables can be used for the service installation. Therefore he connects to the LifeBC backbone. Here the BIM data of the complete building complex is put together. On basis of the 6D pose tracking, data relevant for the area to be operated is selected and transmitted to the mobile device of the technician. The technician uses his mobile system to visualize all these information related to his order to install the new ventilation system. Thereby, the information is geo-referenced and is linked to the addressed building components. Via the multi-sensory semantic-based tracking, the annotations made by the engineer are overlaid with augmented reality visualizations. The technician also gets the information about existing cables and pipes all over the building so that he can check, whether he can use them or plan new pipes and cables, if he needs them. Based on the information of the engineer and his own plans, he can install the ventilation system.
Step 4: Technical documentation
For the documentation, the technician scribbles the cables and pipes he has renewed and completes the information about the service installation and their integration. After finishing his work, he connects to the LifeBC backbone and transmits the information to it.

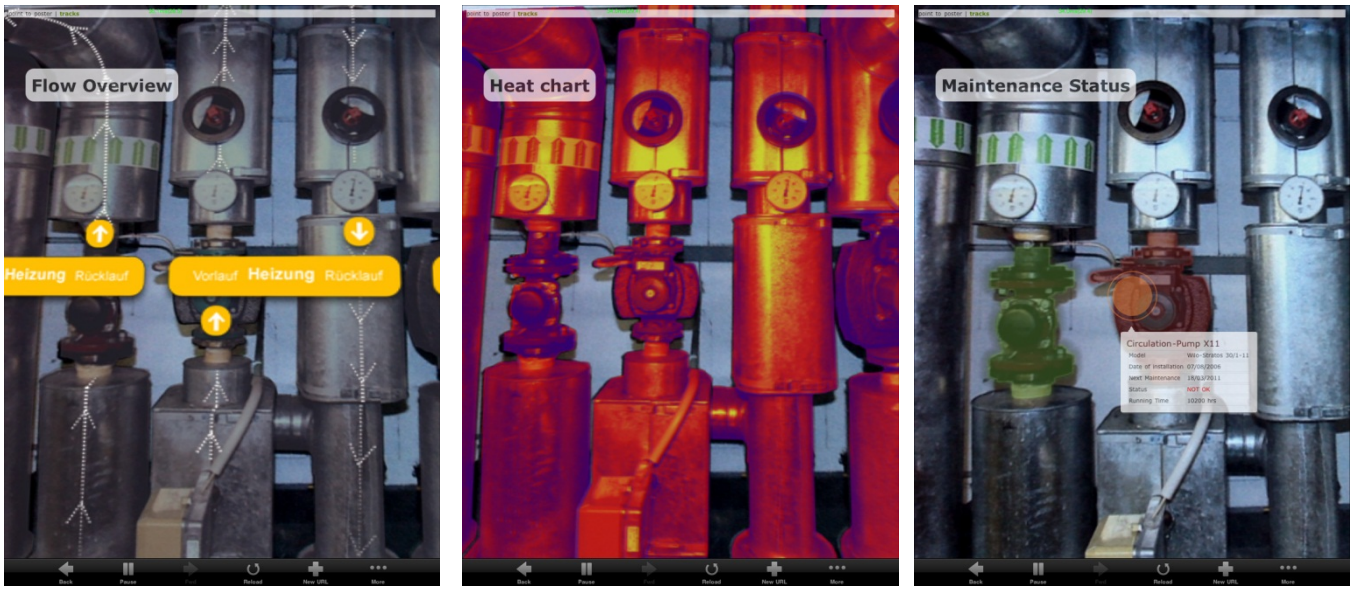

Figure 7. AR visualization of BIM data. Left: Flow overview. Center: Heat chart. Right: Maintenance status.

B. *Use Case: Heating System*

By revealing invisible structures or by depicting abstract numbers, mobile Augmented Reality systems can support building related work tasks. Information can be visually linked to a certain spot or object, without the user's need to preliminary search the BIM databases or prepare properly the wrong information by not knowing the situation at face. Our "heating system" use case addresses these issues. Based on the mobile AR framework described in section IV, we created a demonstrator for this use case, which is shown in Fig. 7 and Fig. 8. This demonstrator uses Apple's iPad 2 with our software system. The iPad features a rear and front camera, has an adequate screen size, supports multitouch input, and is small and lightweight enough to be carried around. In the "heating system" scenario, the facility manager points the iPad on a heating system. The Augmented Reality view depicts data from the BIM database in several layers during the inspection. The first layer depicts the flow overview. Normally physical tags are used to explain certain components. Our system superimposes the flow directions directly on the pipes and explains each component's function additionally (see Fig. 7). The second layer illustrates the current heating condition and the third layer illustrates the (maintenance) status of component parts.

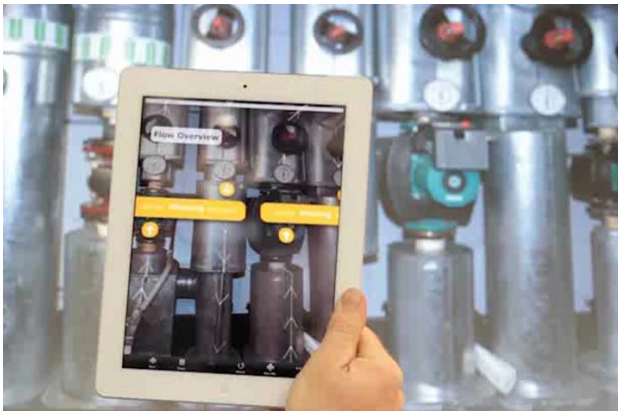

Figure 8. AR maintenance support (on iPad).

In order to facilitate interaction, we integrated a point-and-show selection paradigm, triggered by a centric virtual focal element. The user only needs to point the iPad to the intended part. A color-coding is again depicting the overall status, where red indicates malfunction, orange periodically incidents (like changing a filter or seal) and green proper functionality. A text overlay acts like a virtual tag, which is sticky to each component. It shows all information one would see in the database likewise. With the Augmented Reality feature, the user can visually search and select the data without searching the database manually by arbitrary labels or names. The annotation engine described in section V can be used to add annotations to the heating system's BIM data.

The AR application and the camera pose estimation are processed directly on the mobile device. While a poster tracker is used to showcase this scenario at trade fairs, the physical pipes are tracked with a KLT feature tracker using a reconstructed 3D feature map [23].

VII. Conclusion

We have presented a mobile AR framework as well as an annotation engine, which provide the basis for mobile AR applications that support the building life cycle by integrating virtual information with the real environment. One of the main contributions of the presented system is its flexibility and scalability, as a result of which the distributed BIM AR applications can be realized on arbitrary devices. The presented mobile AR framework supports markerless tracking technologies on mobile devices with different processing powers, both by a client-server based AR infrastructure and by a generic tracking framework for mobile devices whose processing power is fast enough to

handle the necessary calculations themselves. The thorough use of standardized interfaces such as HTTP, HMTL5 and X3D (both for the AR framework and for the annotation engine) ensures a maximal interoperability. The proposed system provides the technological basis for the creation of mobile AR applications which fuse 3D building models with semantic annotations. In addition to the mobile AR framework and the annotation engine, we have provided use cases which show how these technologies could support the building lifecycle management. The combination of BIM with AR offers building related data directly on site and provides the basis for mobile on-site documentation. When presenting the developed technologies (such as the demonstrator shown in Fig. 8), we have received positive feedback. For example, maintenance employees stated that such a system would remarkably simplify their work because they would not need to carry on heavy, printed manuals anymore and that they would not need to tediously search the required information in the paperwork any longer. In future work, it will be interesting to conduct studies which quantitatively evaluate the effects of AR support for building related maintenance and documentation tasks.

We expect that the combination of BIM data with AR will be particularly evident when it comes to the visualization of hidden objects which are part of the BIM data, but not visible in the real world. With mobile AR it becomes possible to see what was built inside a wall, for example the position of water pipes or electrical cables. Due to the steadily increasing availability of building related data, in the future BIM data will not only be accessible for facility managers but also for building inhabitants or house owners. For this new market, markerless augmented reality applications offer a large potential, as they integrate BIM data with the real world and thereby make hidden information intuitively visible.

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