An integrated system for automated construction progress visualization using IFC-Based BIM

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Purpose Accurate and timely visualization of the progress of a construction project is a critical element for success. Current methods of data collection for progress visualization tend to be manual. These manual methods are not only error-prone but also time-consuming. Remote sensing technology has been used to resolve those problems related to collecting the data related to construction progress. Studies have shown that data collected for construction progress visualization via remote sensing technology can be effective. However, data corresponding to all as-built structural components must be collected in order to accurately visualize construction progress. This is impractical on real construction sites that usually are large, cluttered, and complex. This paper proposes an integrated system for the visualization of automated construction progress using IFC-based BIM and data which correspond to parts of as-built structural components acquired using remote sensing technology. **Method** The system integrates measurement, analysis, and visualization of the progress of construction projects in four main modules. The first module extracts geometric and schedule information from IFC and converts the extracted information into a format acceptable to the MATLAB. The second module measures project progress utilizing converted geometric information and 3D data acquired from construction sites. The third module analyzes, verifies, and updates project progress using schedule sequences and topological information in IFC. The last module compares the as-built and as-planned schedules and visualizes current project progress. **Results & Discussion** The proposed integrated system has been verified to demonstrate its robustness by using data corresponding to a part of as-built structural components acquired from real construction sites. The result reveal that the proposed integrated system can accurately and effectively visualize current project progress information from data which correspond to part of as-built structural components. The visualization results can be used as a decision-making tool by project stakeholders.

Keywords*: automation, industry foundation classes, progress visualization*

INTRODUCTION

It has been shown that accurate construction progress measurement is critical to the success of a building project[1, 2, 3]. Recently, studies have demonstrated that remote sensing technology can be used to obtain 3D data about construction progress and have proven the efficiency of the data collection process[1, 3]. In addition, 3D data acquired using remote sensing technology can be effectively compared with the building project's 4D as-planned building information model (BIM), which integrates an as-planned schedule with a 3D model created using computer-aided design (CAD)[4, 5]. By doing this, one can obtain construction progress information automatically from the construction site.

Previous studies have shown the possibility of construction progress measurement automatically by using remote sensing technology. However, the accuracy of the construction progress measurement is affected by a number of factors. First, because of the sensor's limited field of view, it is only possible to obtain 3D data corresponding to the as-built structural components that are located within this field of view[3]. Second, in any building project, the structural components are arranged with some level of complexity, and there are likely to be various pieces of equipment and other objects located around the construction site. Thus, structural components that are physically within the sensor's field of view may nonetheless be blocked from the sensor's view[1, 3, 4]. For these reasons, 3D data obtained by using remote sensing technology is incomplete. A study by Bosché[1] found that only 83% of actual as-built steel components were recognized as such. In a study by Son and Kim[3], 88% (86 of 98) steel components were recognized as such. In research by Golparvar-Fard et al.[4], part of an as-built wall was not recognized as such. In a study by Turkan et al.[5], 98% of as-built concrete components were recognized as such. In order to resolve these problems, a process that includes obtaining a large number of 3D data sets from different positions and then merging them should be performed. However, merging multiple sets of data alone is not enough: The Son and Kim[3], Golparvar-Fard et al.[4], and Turkan et al.[5] experiments used this method during the construction of a simple, small structure. Though accurate data about structural components was obtained, the method still failed to obtain complete 3D data. Thus, in the case of a larger or more complex construction project, it is impossible to obtain complete data. Therefore, the above-mentioned problems will significantly affect one's ability to obtain construction progress information.

This study proposes a verification process for construction progress measurement through utilizing information in a BIM to modify inaccurate construction progress information caused by incomplete 3D data. Methodologies related to construction progress measurement are provided in Section 2. In Section 3, field experiment results obtained by using the proposed verification process are presented. Finally, conclusions and recommendations for future research are provided in Section 4.

METHODOLOGY

Information extraction

In order to initiate the measurement of construction progress, relevant as-planned information from an IFC-based BIM and relevant as-built information from 3D data obtained by remote sensing technology should be extracted. IFC (Industry Foundation Classes) is a data model standard developed by BuildingSMART International Ltd. as an international information exchange standard. IFC2x Edition 3 (IFC2x3) is the latest official IFC release; it contains 653 entities and allows for complex relationships between these entities. Among the 653 entities in IFC2x3, entities that contain as-planned information for construction progress measurement should be filtered and mapped to the internal information structure within the data processing software. Also, 3D data obtained from the construction site using remote sensing technology contains not only as-built information for the building project itself but also for various objects at the construction site such as heavy equipment, materials, and so on. In terms of construction progress, as-built information refers to structural components. Therefore, a process called "structural component detection" is performed to extract 3D data about the building project's structural components from the overall set of 3D data obtained from the construction site.

Extraction of as-planned information for construction progress measurement from an IFC-based BIM

To filter and map as-planned information for construction progress measurement to the internal information structure, entities that contain the geometric information for each structural component, the list of components related to each activity, the planned schedule of activities, the sequence that activities are executed in, and the spatial relationship between components should be defined. Among the 653 entities in an IFC file, IfcColumn, IfcBeam, IfcSlab, and IfcWall are the entities that represent the most basic structural components. Fig. 1 shows an example of the geometric information for a column in an IFC file. The entity IfcColumn (#473) associates IfcLocalPlacement (#438) with IfcProductDefinitionShape (#472). The number in parentheses represents the instance number in the IFC file in the figure. IfcLocalPlacement (#438) is used to define the placement of a component in relation to the placement of another component. IfcProductDefinitionShape (#472) contains the entity IfcShapeRepresentation (#471), which is used to define a specific kind of representation which represents a component shape. In this example, component shape is represented by IfcFacetedBrep (#443), the entity that defines boundary representation (B-rep). B-rep represents a component indirectly by its bounding surface[6]. Surfaces that represent the component are defined by IfcClosedShell (#444), and the boundaries of each surface are defined by IfcFace (#455), which contains the entity IfcFaceOuterBound (#454). IfcPolyLoop (#453), which is contained within IfcFaceOuterBound (#454), is used to define the 3D coordinates of the boundaries of each surface. In the example shown in Fig. 1, the column consists of six surfaces (#455, #458, #461, #464, #467, and #470). In the case of IfcFace (#455), this particular surface consists of four boundaries and its 3D coordinates are (63231.5, -33226.625, 5000), (63931.5, -33226.625, 5000), (63931.5, -33926.625, 5000), and (63231.5, -33926.625, 5000). Thus, the geometric information for each component is extracted from the IFC file by integrating the 3D coordinates of each boundary of the surfaces defined by IfcClosedShell.

After the geometric information for each structural component is defined, activity information related to each component should be defined to generate a 4D as-planned model. Activity information used to generate a 4D as-planned model includes the components related to the activity and the planned schedule of activities. Fig.2 shows an example of the activity information related to each component in an IFC file. First, the components related to the activity are defined by IfcRelAssignsToProcess[7]. IfcRelAssignsToProcess (#3646) includes the list of entities -- such as IfcColumn (#473), IfcColumn (#1487), and IfcTask (#3605) -- that connect an activity with its components. The figure shows that IfcTask (#3605) is related to IfcColumn (#473), IfcColumn (#1487), IfcColumn (#1283), IfcColumn (#1706), IfcColumn (#1541), IfcColumn (#1651), and IfcColumn (#1596).

```
#473= IFCCOLUMN('0tYOoB2YL7Zww7$Yv9gmpX',#5,'M_Rectangular Column:700 x 700mm:700 x 700mm:110976_(#240)',$,$,#438,#472,$);
  #438= IFCLOCALPLACEMENT(#25,#439);
  #472= IFCPRODUCTDEFINITIONSHAPE($,$,(#471));
    #471= IFCSHAPEREPRESENTATION(#21,'Body','Brep',(#443));
      #21= IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.E-5,#20,$);
        #20= IFCAXIS2PLACEMENT3D(#19,$,$);
          #19= IFCCARTESIANPOINT((0.,0.,0.));
      #443= IFCFACETEDBREP(#444);
        #444= IFCCLOSEDSHELL((#455,#456,#461,#464,#467,#470));
          #455= IFCFACE((#454));
            #454= IFCFACEOUTERBOUND(#453,.T.);
              #453= IFCPOLYLOOP((#445,#446,#447,#448));
                #445= IFCCARTESIANPOINT((63231.5,-33226.625,5000.));
                #446= IFCCARTESIANPOINT((63931.5,-33226.625,5000.));
                #447= IFCCARTESIANPOINT((63931.5,-33926.625,5000.));
                #448= IFCCARTESIANPOINT((63231.5,-33926.625,5000.));
```

Fig. 1. An example of the geometric information for a column in an IFC file

```
#3646= IFCRELASSIGNSTOPROCESS('22$uY6rHDSwjIIqCLDSAT',#5,$,$,(#473,#1487,#1283,#1706,#1541,#1651,#1596),$,#3605,$);
  #473= IFCCOLUMN('0tYOoB2YL7Zww7$Yv9gmpX',#5,'M_Rectangular Column:700 x 700mm:110976_(#240)',$,$,#438,#472,$);
  #1487= IFCCOLUMN('0pGRy$KyP6BvN7M$MuGx_d',#5,'M_Round Column:900mm Diameter:122552_(#607)',$,$,#1302,#1486,$);
  #1283= IFCCOLUMN('1Lt26C2CDFwOflLCF5X0a',#5,'M_Round Column:900mm Diameter:122264_(#580)',$,$,#1098,#1282,$);
  #1706= IFCCOLUMN('0XaD1N4dv4eOy02RMuly$I',#5,'M_Rectangular Column:700 x 700mm:125108_(#719)',$,$,#1671,#1705,$);
  #1541= IFCCOLUMN('2KbTYZRCTA3eBpD9CBwFV',#5,'M_Rectangular Column:700 x 700mm:123388_(#634)',$,$,#1506,#1540,$);
  #1651= IFCCOLUMN('2PdsFWyBD1a8a25ep32u8o',#5,'M_Rectangular Column:700 x 700mm:124670_(#690)',$,$,#1616,#1650,$);
  #1596= IFCCOLUMN('2uhfRvArDIfRLZ6arMICz',#5,'M_Rectangular Column:700 x 700mm:124194_(#662)',$,$,#1561,#1595,$);
  #3605= IFCTASK('2ymfpBWwj0kgb42nCKDAxV',#5,'Column','1',$,'ST00020',$,$,.F.,$);
#3616= IFCRELASSIGNSTASKS('0AW4NVwqb0XQjqEVn_5smS',#5,$,$,(#3605),$,#3591,#3606);
  #5= IFCOWNERHISTORY(#4,#2,$,.NOCHANGE.,$,$,$,1326293360);
  #3605= IFCTASK('2ymfpBWwj0kgb42nCKDAxV',#5,'Column','1',$,'ST00020',$,$,.F.,$);
  #3591= IFCWORKSCHEDULE('17YNEOqr92rPu4kgAY7MW_',#5, $,$,$,'Synchro-WS-1FD2EB5C',#3604,$,$,$,$,#3598,$,$,$);
    #3604= IFCDATEANDTIME(#3602,#3603);
      #3602= IFCCALENDARDATE(11,1,2012);
      #3603= IFCLOCALTIME(23,49,$,$,$);
    #3598= IFCDATEANDTIME(#3596,#3597);
      #3596= IFCCALENDARDATE(11,1,2012);
      #3597= IFCLOCALTIME(9,0,$,$,$);
  #3606= IFCSCHEDULETIMECONTROL('3SdyVu0dH6mOpIUSHeHUVE',#5,$,$,$,$,$,#3615,#3609,$,$,$,#3612,432000.,$,$,$,$,$,$,$,$,$,$);
    #3615= IFCDATEANDTIME(#3613,#3614);
      #3613= IFCCALENDARDATE(11,1,2012);
      #3614= IFCLOCALTIME(9,0,$,$,$);
    #3609= IFCDATEANDTIME(#3607,#3608);
      #3607= IFCCALENDARDATE(11,1,2012);
      #3608= IFCLOCALTIME(9,0,$,$,$);
    #3612= IFCDATEANDTIME(#3610,#3611);
      #3610= IFCCALENDARDATE(31,1,2012);
      #3611= IFCLOCALTIME(17,0,$,$,$);
```

Fig. 2. An example of the activity information in an IFC file

Second, the planned schedule of activities is defined by IfcRelAssignsTasks[7, 8]. IfcRelAssignsTasks (#3616) provides the as-planned schedule of activities by linking IfcTask (#3605), which is used to define the properties of a particular activity, and IfcScheduleTimeControl (#3606), which is used to define the scheduled start date, scheduled finish date, and scheduled duration of IfcTask (#3605). According to the example shown in Fig. 2, the scheduled start date is defined by IfcDateAndTime (#3609) as January 11, 2012 at 9:00 am; the scheduled finish date is defined by IfcDateAndTime (#3612) as January 31, 2012 at 5:00 pm; and the scheduled duration is 432,000 seconds.

An IFC-based BIM contains not only information for generating a 4D as-planned model but also information that can be used to verify the logical relationship between structural components such as the sequence that activities are executed in and the spatial relationship between components. Fig. 3 shows an example of the logical relationship between the structural components defined in an IFC file. The sequence that activities are executed in is defined by IfcRelSequence[9]. IfcRelSequence (#3644) represents the sequence that activities are executed in as the relationship between two activities. In order to define the relationship between two activities, IfcRelSequence (#3644) associates the relating activity, the related activity, the time lag between the two activities, and the sequence type. In this example, the relating activity (taken from Fig. 3) is IfcTask (#3605), the related activity is IfcTask (#3617), the time lag is 0 seconds, and the sequence type is "finish to start" (Finish_Start). This means that when IfcTask (#3605) is finished, IfcTask (#3617) will start and there will be no time lag between IfcTask (#3605) and IfcTask (#3617). The spatial relationship between components is defined by IfcRelConnectsElements[10]. In order to define connectivity, which describes two elements being physically or logically connected, IfcRelConnectsElements (#3654) specifies the relationship between a relating component and a related component. According to the example in Fig. 3, IfcColumn (#473), which is the relating component, and IfcBeam (#1816), which is the related component, are connected.

Extraction of as-built information for construction progress measurement from 3D data

In order to extract 3D data about structural components from the overall set of 3D data obtained from the construction site, color-model-based concrete detection using machine learning algorithms proposed by Son et al.[11] was used. Son et al.[11] showed that combining the hue-saturation-intensity (HSI) color space with the support vector machine (SVM) proposed by Vapnik[12] is useful for detecting concrete in color images. In this method, the database is transformed from red-green-blue (RGB) to HSI, and then a concrete color-model is constructed using SVM. Using the concrete color-model, 3D data corresponding to the concrete's color is classified and extracted from the 3D data obtained from the construction site.

```
#3644= IFCRELSEQUENCE('0oxdnhc51COeH5EYjzvF3f',#5,$,$,#3605,#3617,0.,.FINISH_START.);
  #3605= IFCTASK('2ymfpBWwjGkgb42nCKDAxV',#5,'Column','1',$,'ST00020',$,$,.F.,$);
  #3617= IFCTASK('00OF8b0fP4duA_nzVTIQ3Q',#5,'Beam','2',$,'ST00030',$,$,.F.,$);
#3654= IFCRELCONNECTSELEMENTS($,#5,$,.F.,.F.,$,#473,#1816);
  #473= IFCCOLUMN('0tYOoB2YL7Zww7$Yv9gmpX',#5,'M_Rectangular Column:700 x 700mm:110976_(#240)',$,$,#436,#472,$);
  #1816= IFCBEAM('2lnPQcl392kx6BPgyl8AHP',#5,'M_Concrete-Rectangular Beam:500 x 550mm:127918_(#752)',$,$,#1781,#1815,$);
```

Fig. 3. An example of the logical relationship between structural components in an IFC file

Construction status recognition

After the information extraction process, a 4D as-planned BIM and 3D data about each structural component is used to recognize the construction status of each structural component. The process to recognize the construction status of each component consists of two stages: The first stage is 3D registration, which aligns the 4D as-planned BIM with 3D data about structural components, and the second stage involves matching the 4D as-planned BIM with 3D data about structural components to recognize constructed structural components. The 3D registration was performed by the approach proposed by Kim et al.[13]. This approach provides a fully automated way to align 3D data with a 3D CAD model. The approach requires preprocessing for the 3D data and the 3D CAD model, respectively. After the preprocessing, the aligning of the preprocessed 3D data with the preprocessed 3D CAD model consists of two distinct steps: global registration and local registration. Then, by applying the transformation parameter determined by the global and local registration of the preprocessed 3D data, the coordinates of the original 3D data and the original 3D CAD model can be directly aligned.

Based on the registration result, a matching method that uses SVM is then used to recognize construction status. This method provides accurate results for construction status recognition regardless of the density of the 3D data. In this method, for each structural component, a subset of 3D data that represents that component is extracted from the overall 3D data set that has undergone 3D registration. Then, each subset of 3D data is classified according to predicted categories using SVM. The construction status of each component is then updated as follows:

$$S_k = \begin{cases} 1, & \text{if } A_k = P_k \\ 0, & \text{otherwise} \end{cases}$$

where S_k is the construction status of the k th component; $k = \{1, ..., l\}$, where l is the total number of components; A_k is the actual category of the k th component; and P_k is the predicted category of the k th component.

Construction status verification

The construction status of each structural component obtained through the aforementioned process may be inaccurate when the 3D data is incomplete. Thus, in order to measure construction progress accurately, a verification process is needed to modify the inaccurate construction status of any such component when that inaccurate status is caused by incomplete data. This verification process consists of two stages: Verification using the sequence that activities are executed in and verification using the spatial relationship between structural components. In verification using the sequence that activities are executed in, the construction status of structural components belonging to a preceding activity is modified. However, verification using the sequence that activities are executed in cannot modify the construction status of components belonging to the same activity. Hence, verification using the spatial relationship between structural components is necessary to modify the construction status of components belonging to the same activity. Through these two verification processes, it is possible to modify the inaccurate construction status of any such component.

Verification using the sequence that activities are executed in

The input for the first verification process is the construction status of each structural component obtained through the aforementioned process and the sequence that activities are executed in. IfcRelSequence defines preceding and following activities. This relationship means that a following activity will start when the corresponding preceding activity has completed. Thus, if at least one structural component related to a following activity is recognized as being constructed, all components related to the preceding activity are recognized as being constructed. Algorithm 1 uses the construction status of structural components related to a following activity to determine the construction status of components related to a preceding activity. The details of Algorithm 1 are given below:

Algorithm 1: Algorithm for verification using the sequence that activities are executed in

1: Input: The construction status of each structural component and the sequence that activities are executed in, taken from IfcRelSequence in the IFC file.
2: Get the construction status of the structural components that are contained within the first IfcRelSequence, using the SVM matching method.
3: The modified construction status is derived from:

$$A_p(S_i)=\begin{cases} 1, & \text{if } \sum A_f(S_j) \geq 1 \\ A_p(S_i), & \text{otherwise} \end{cases}$$

where $A_p(S_i)$ is the construction status of the i th component of the preceding activity; $i=\{1,...,n\}$, where n is the number of components related to the preceding activity; $A_f(S_j)$ is the construction status of the j th component of the following activity; and $j=\{1,...,m\}$, where m is the number of components related to the following activity.
4: Get the construction status of the structural components that are contained within the next IfcRelSequence, using the SVM matching method.
5: Repeat steps 3 and 4 until every IfcRelSequence has been checked.

Verification using the spatial relationship between components

The input for the second verification process is the modified construction status of each structural component obtained from Algorithm 1 and the spatial relationship between structural components. IfcRelConnectsElements represents the spatial relationship between structural components by defining relating and related structural components. This relationship shows the logical or physical relationship between a relating and a related structural component. If a related component is considered to be constructed, all corresponding relating components are considered to be constructed. Algorithm 2 uses the construction status of a related component to determine the construction status of a relating component. The details of Algorithm 2 are given below:

Algorithm 2: Algorithm for verification using the spatial relationship between structural components

1: Input: The construction status of each structural component that was modified by Algorithm 1 and the spatial relationship between structural components, taken from IfcRelConnectsElements in the IFC file.
2: Get the construction status of the related structural components contained within the first IfcRelConnectsElements, using Algorithm 1.
3: The modified construction status is derived from:

$$R_g=\begin{cases} 1, & \text{if } R_d = 1 \\ R_g, & \text{otherwise} \end{cases}$$

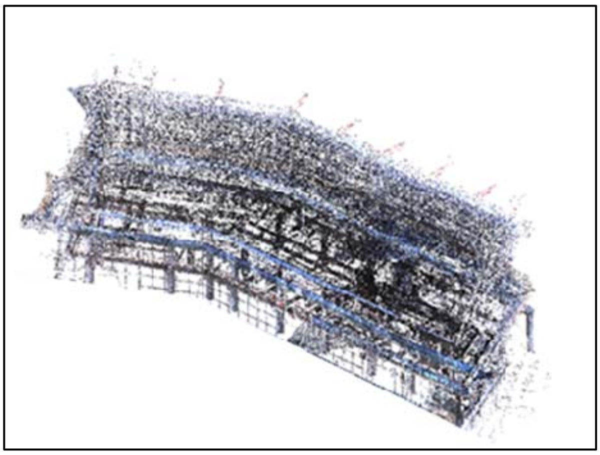
where R_g is the construction status of the relating component and R_d is the construction status of the related component.
4: Get the construction status of the related structural components contained within the next IfcRelConnectsElements, using Algorithm 1.
5: Repeat steps 3 and 4 until every IfcRelConnectsElements has been checked.

FIELD EXPERIMENT

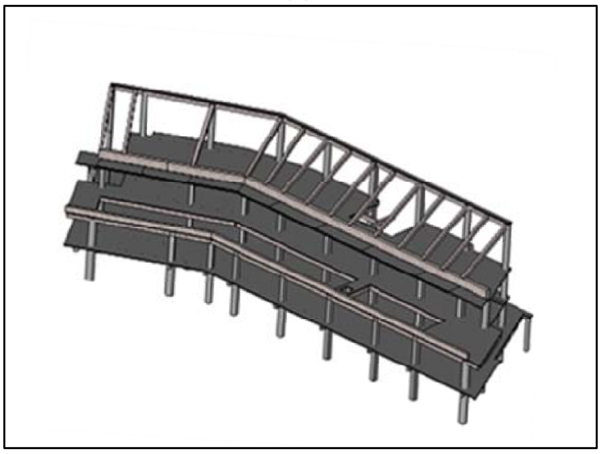
To evaluate the improvement in accuracy of construction progress measurement when the 3D data obtained from the construction site has undergone the proposed verification process, a field experiment was conducted. The field experiment was conducted on a four-floor new concrete building under construction in South Korea. Of the four floors, three of them were constructed at the time of the field experiment. 3D data was obtained from the construction site by using a laser scanner to take eleven scans from different positions at ground level.

The eleven scans were then merged to obtain the overall set of 3D data from the construction site. Fig. 4(a) shows the merged 3D data from the eleven scans obtained from the construction site. To generate the BIM, Autodesk Revit™ (developed by Autodesk, Inc.) was used. Synchro (developed by Synchro Ltd.) was used to link the 3D geometric information of the building in the BIM with scheduling information and to export the BIM to the IFC file. The BIM used for the experiment is shown in Fig. 4(b).

The accuracy of construction progress measurement was measured by recall and precision rates. The recall rate is the percentage of structural components recognized as being constructed among actually constructed components. The precision rate is the percentage of actually constructed components among components that are recognized as being constructed. As shown in Table 1, the verification process consists of two steps that improve the accuracy of construction progress measurement, especially the recall rate. Without the verification process, the recall rate is very low since actually constructed internal columns and beams under the slab are recognized as being non-constructed because these components are blocked from the sensor's field of view. Through the first verification step, the recall rate is significantly improved since actually constructed components in the first and second floor are recognized as being constructed. In the second verification step, the construction status of components in the third floor is modified. The recall rate in this study is higher than in previous research. For example, in our previous research, the recall rate was 88% without the verification process[3].



(a)



(b)

Fig. 4. (a) Merged 3D data from eleven scans obtained from construction site using a laser scanner; (b) The BIM used for the experiment

These current results indicate that the proposed verification process can improve the accuracy of construction progress measurement that is affected by incomplete 3D data caused by the limitations of the sensor's field of view and the occlusion of structural components.

Table 1. Effect of verification process on accuracy of construction progress measurement

	Recall rate	Precision rate
Without verification results	52%	100%
With first verification results	95%	100%
With second verification results	100%	100%

CONCLUSIONS AND FUTURE WORK

This study presented a verification process that uses information contained in an IFC-based BIM to improve inaccurate construction progress measurement caused by incomplete 3D data obtained from a construction site using remote sensing technology. To extract information for improving the accuracy of construction progress measurement, information that is needed for the recognition of each structural component's construction status and for the verification process was defined. Based on the extracted information, the initial construction status of each component was recognized. The initial construction status of each component may be inaccurate due to incomplete 3D data. Therefore, verification using the sequence that activities are executed in (for components related to different activities) and verification using the spatial relationship between components (for components related to the same activity) was performed. The improvement in accuracy due to the proposed verification process was validated using incomplete 3D data obtained from a real construction site. The results indicate that the proposed verification process is capable of improving the accuracy of construction progress measurement; thus, construction progress can be effectively managed. In future research, the proposed verification process should be employed in various applications of construction progress management. Examples of such applications include construction progress visualization, actual progress calculation, and construction of an automated construction progress management system.

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