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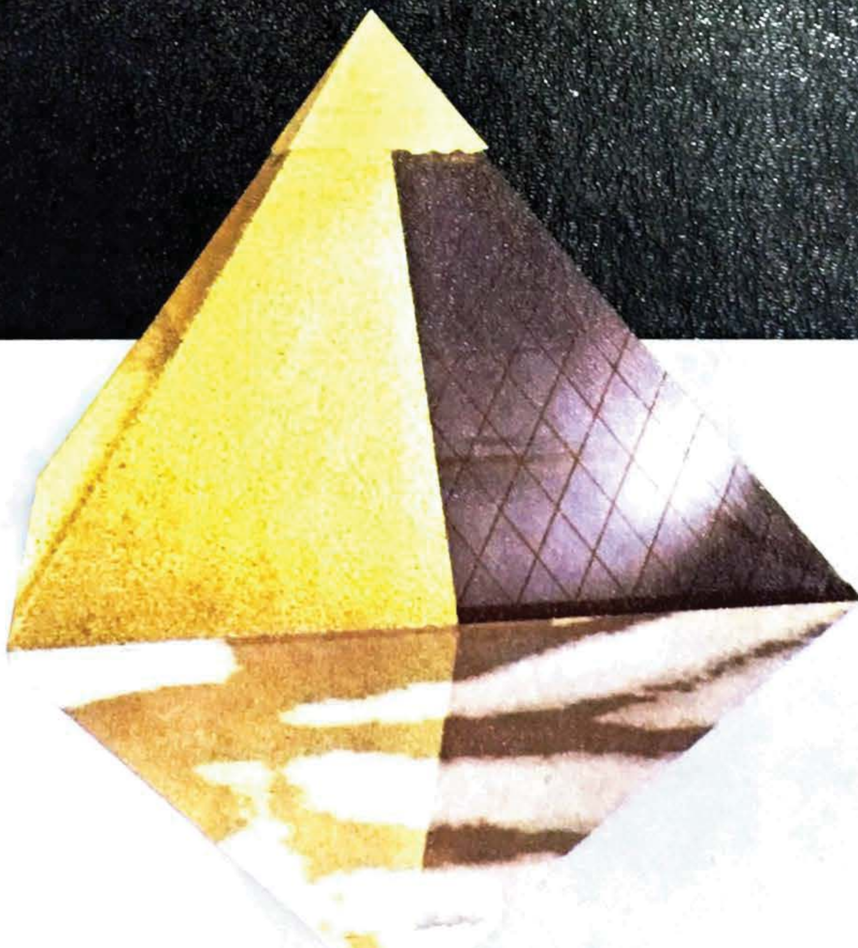

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An automated stereometric knowledge-based CAD system for construction management

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Abstract

This paper presents a computer-aided construction management system that has been developed which combines a knowledge-based Computer-Aided Design (CAD) system; a data-base construction estimating, planning, monitoring, updating, and payments determination techniques; and a stereometric close-range photogrammetric technology for updating and inspecting surface measurements progress. The theme is to automate quantity take-off and payment estimation processes before and during construction through linking design data to construction plans. The system is a step toward automation of construction management procedures and of monitoring the geometry of engineering construction.

1 Introduction

Computer vision technology, using stereometric photogrammetric systems equipped with sensors such as Charge-Coupled-Device (CCD) cameras, has the capability of high accuracy, ease-to-use, as well as real-time potential for useful surface measurements extraction. This potential will be assured when proper camera calibration technique is used. Although CCD cameras have some limitations such as their limited field of view and resolution, they can be controlled by using larger scales for captured stereo images. Thus, CCD cameras could provide a real-time three-dimensional (3-D) input for CAD software about the project status.

Different research activities have been made to utilize photogrammetric methods to reconstruct 3-D geometric architectural objects and relate their data into CAD. Rogers and Bennett [6] found a mechanism for connecting existing encoded stereoplotter to CAD software. Whereas, Streilein [7] used S-VHS camcorder and digital photogrammetric station to create 3-D geometry features and pass these features into a data-structure useful for CAD. Stereoscopic image pairs have also been used to model automatically complex scenes like buildings [3,4]. Yet, introducing a system which combines stereo vision, CAD, and construction management using a knowledge-based umbrella is still crucial for further step toward automation.

The work presented in this paper is motivated by the great deal of redundancy between management tasks of estimating, planning, and controlling. Performing quantity take-off for estimating and bidding purposes, work breakdown of the project into activities, and measuring work progress for payments and control purposes can all be defined in term of project specific components. This work is also motivated by the great deal of redundancy among and between projects. While each project has a distinct design, the majority of construction projects have similar and typical composition. Concrete footings, for example, are common in most projects, and while they may differ in dimensions and reinforcing, they are similar in specifications. Further the quantity of concrete components of any footing can be easily expressed in terms of the footing's dimensions.

A realistic integrated construction planning and control model must use the disparate construction management data as is provided by the design drawings and specifications and relate this data to the construction plan; pay items, units, and prices; and work progress. The integration of CAD knowledge-based system with stereometric vision as well as object-oriented construction management for the whole stages of project work, including: project definition, planning phase, and construction phase have the right direction toward an automated CAD-based construction management system. The main objective of this paper is to present such an integrated system. The following sections present the developed system.

2 Project Definition Phase

Model formulation starts with a user input of project definition. The user defines the project design through CAD drawings, which when drawn to scale provide the dimensions of each of design components [1]. Using object oriented programming paradigm, each of the user-drawn components is an instant of a class with specific attributes that defines its design data (e.g. composition and dimensions) and specifications (i.e. the required type of materials and workmanship). The user defines these classes as specialized classes of the expandable class hierarchy of typical construction components included in the system. A design component can be simple or compound. Simple components represent basic construction materials such as steel and concrete while compound components represent design elements such as footings, columns, and slabs [5].

For automated project definition, the user draws to scale the project components as CAD blocks and defines relevant attributes and saves them in a database file. The attributes required by the system are *name*, *class*, *dx*, *dy*, and *dz*. *Name* serves to relate the design element to its material components. For a design element, *name* is a unique identification code. For a material component of a design element, *name* is the design element's code. *Class* is the class of which the drawn project component is an instant. *dx*, *dy*, and *dz* are the dimensions of the component which can be extracted from the drawings. They serve to calculate length, area, or volume of regularly shaped components. Therefore, only the dimensions used in the calculations need to be defined. For example, plastering, which is typically measured by area, only two dimensions need be defined. Reinforcing bars, which are measured by weight as a function of volume, *dx* and *dy* stand for the bar length and diameter, respectively.

Figure 1 shows plan, side, and isometric views of CAD drawings for a typical reinforced concrete frame room. The figure shows the design of the footings, tie beams, columns, hollow brick walls, and slab elements. Each of these elements is a CAD block of distinct attribute values. For example, the four footings are instances of the Footing class. Each of these footing is drawn by recalling and scaling the predefined FOOTING block. Figure 2 shows one of the large footings, in Figure 1, of attributes Footing, Ftg1, 2.0, 2.0, and 0.5 for *class*, *name*, *dx*, *dy*, and *dz* respectively. The second large footing has the same attributes except for *name*. However, other footings have different attributes. The reinforcing bars of each footing are instances of the Rebar class and are drawn by recalling and scaling the predefined REBAR block of *name*, *class*, length (*dx*), and diameter (*dy*). For example, Ftg1 contains 10 longitudinal and 10 traversal bars. Because these bars are identical, the user need only to recall and scale one block and define its attributes of Ftg1, Rebar, 1.9 and 16 for *name*, *class*, length and diameter respectively. The user can draw the remaining bars as copies of the one defined earlier. Notice here that the *name* attribute (Ftg1) is the identification name of the footing of which the bar is a component.

After completing the CAD drawings of a project, the user saves the attributes of the project components into a single database file. The fields of this data base file are the *name*, *class*, *dx*, *dy*, and *dz* attributes, and the attributes of each component constitute a record in the database file. Therefore, a component block can have up to three dimensional attributes.

The database file provides the input needed for the planning phase of the project which is carried out by an object oriented planning model.

3 Planning Phase

After project definition, the user recalls the database file (the output of the project definition phase). This results in an object oriented format of interrelated project components with distinct attributes. The user then relates the project components to the pay items, units, and prices as given by the contract documents. Finally, the user defines the construction plan and relates it the project specific components.

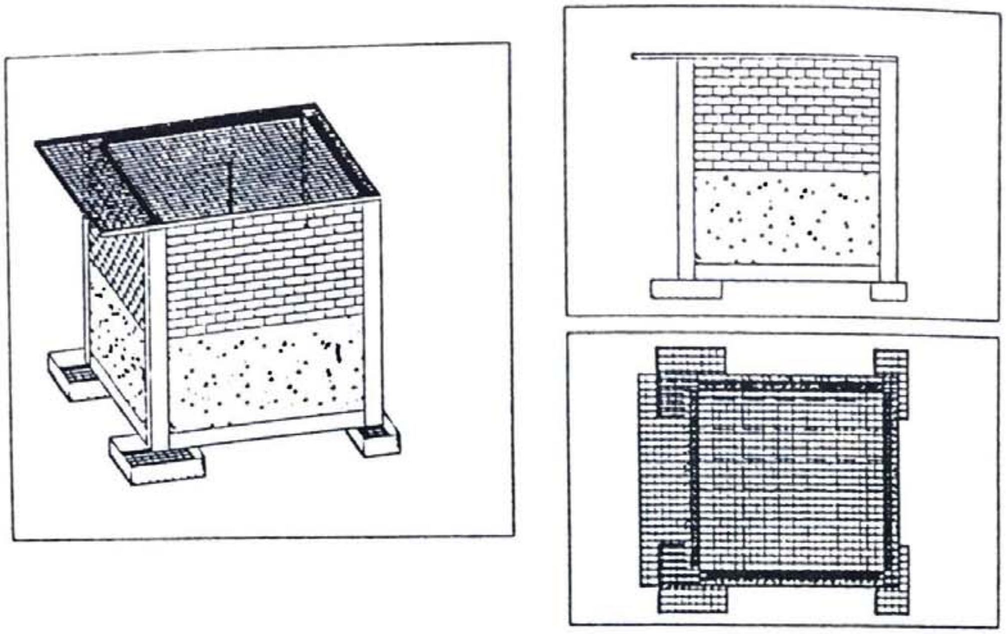

Figure 1. Plan, side, and isometric views of CAD drawings.

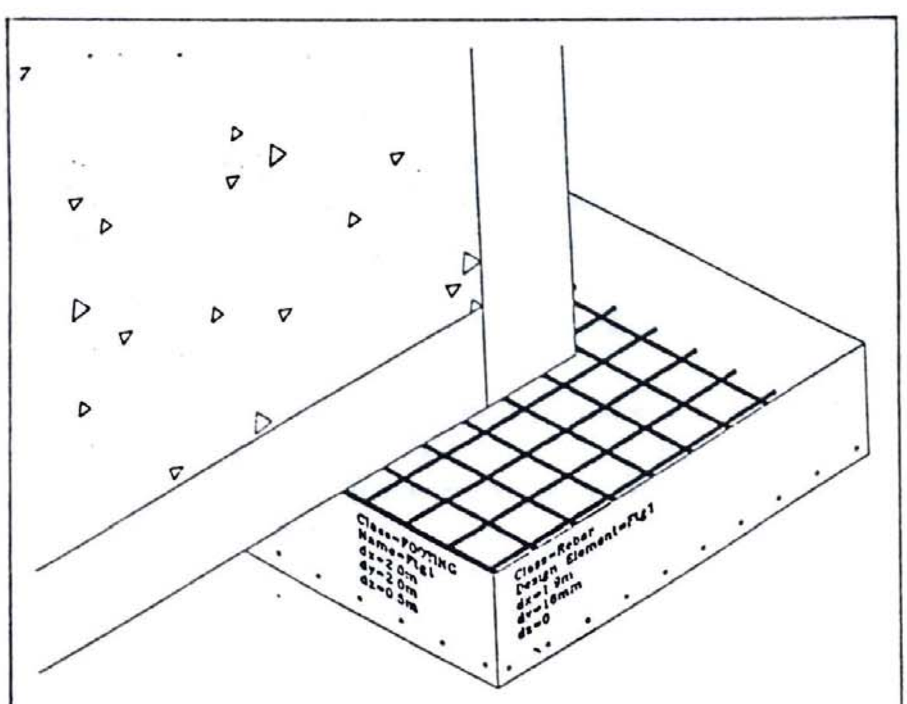

Figure 2: Block attributes of design components.

The pay items are related to the project components through their classes. They could be of a specific class such as 3KsiConcrete or of a generic class such as Concrete for all the components of the 3KsiConcrete and 4KsiConcrete classes which specialize the Concrete class. The pay units could be of length, area, volume, weight, or lump-sum.

The construction plan is Critical Path Method (CPM) like network of construction activities required to construct the project. Each activity has a unique user defined identification number, name, duration, precedence, target start, and scope. Duration is deterministic and defines the time units required to complete the activity. The precedence relationship is finish-to-start whereby the start of an activity is conditional upon the completion of all its predecessors. Target start defines the earliest time the activity can start based on technical or managerial constraints and is defaulted to the activity early start. The scope of an activity serves to relate the construction plan to the project components and is defined by user input of the design elements to which it applies and the class of material components of those design elements to be processed in the activity.

4 Construction Phase

The system is augmented with a stereometric vision system that provides automated input of progress for the project status in terms of surface measurements. The function of this system is to update the status of the project components defined in the project definition phase through stereo vision surface measurements monitoring for components which have measurement units.

Human visualization of images might be needed for other components such as painting. The surface measurements obtained from the stereometric vision need not be complete or extensive. This is because the planning model induces the status of construction components through the precedence relationships between the construction activities. For example, the cast concrete activity is preceded by the place rebars activity. Once the status of concrete component of a design element is known, the status of reinforcing bars in the design element will also be known.

The stereometric vision scheme which has been developed for this phase is shown in Figure 3. It starts with capturing stereo images, using pre-calibrated cameras, for different construction site scenes in order to form different stereo models. Each two adjacent stereo models should have control points in between for the purpose of linking stereo models into a uniform 3-D coordinate system. Commonly, solid-state cameras are used for image capturing because of their geometric fidelity as well as real-time potential. The basic methodology of the scheme could also be done using film-based cameras, but digitization process of images is required to have digital image format. The cameras are mounted on an adjustable stage to have a suitable field of view as well as to assure common overlapping area between adjacent stereo models. The conjugate image coordinates of different stereo models could then be measured after displaying digital images on computer screen. Model coordinates of each stereo model could be computed using special intersection algorithm. Then linking between stereo models coordinates is performed as will be shown in the following section.

4.1 CAD and Vision Coordinates Transformation

After the extraction of the (x, y, and z) coordinates of different sequential stereo models of different scenes of construction site, mathematical modeling of the relationship and linking between different coordinate systems of these stereo models have to be accomplished. This will introduce a consistent ground-based referenced 3-D coordinate system for the construction site for all the captured stereo models (to be called as stereo vision coordinate system). Another relationship between vision and CAD coordinate systems has to be established. The vision coordinate system has to be scaled, translated, and rotated with respect to the CAD coordinate system. Referring to Figure 4, assuming that (x_j, y_j, and z_j) represent the computed vision coordinates of point j, and (X_j, Y_j, and Z_j) be the coordinates of the same point in the CAD coordinate system. The basic transformation equations describing the relationship between the two 3-D coordinate systems could be expressed as in the following projective equations:

$$\begin{bmatrix} X_j - X_o \\ Y_j - Y_o \\ Z_j - Z_o \end{bmatrix}_{(3*1)} = \lambda [M]_{(3*3)} \begin{bmatrix} x_j \\ y_j \\ z_j \end{bmatrix}_{(3*1)} \qquad (1)$$

where

λ is the scale factor

(X_o, Y_o, and Z_o) are three translation parameters; i.e. coordinates of the origin (o) of the vision coordinate system.

M is the orthogonal orientation matrix which is function of the rotation angles (ω, φ, and κ) around the (x, y, and z) axes of the vision coordinate system, respectively as shown in the following equation:

$$[M]_{(3*3)} = \begin{bmatrix} \cos Xx & \cos Yx & \cos Zx \\ \cos Xy & \cos Yy & \cos Zy \\ \cos Xz & \cos Yz & \cos Zz \end{bmatrix}_{(3*3)} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}_{(3*3)} \qquad (2)$$

CosXx, CosYx, ..., CosZz (i.e. m_{11}, m_{12}, ..., m_{33}) are cosines of the space angles between the respective stereo vision axes and CAD axes.

Same set of transformation equations does exist between every adjacent stereo images (models) coordinate systems. Each known CAD control point gives rise to one set of equations like in equation (1) when its vision coordinates are measured. The transformation equations have seven unknowns: scale (λ), three rotation angles (ω, φ, and κ), and three translation parameters (X_o, Y_o, and Z_o). Consequently, a minimum of three control points in the vision model area are needed to perform this transformation procedure [2]. In case of more control points than required, a weighted least-square solution has to be performed and thus the set of equations have to be linearized.

Computer software has been developed to perform this coordinate transformation. The software algorithm accepts control types which are redundantly available in construction site such as: point location, distances, elevation differences, and verticality of windows, doors, or walls.

5 System Output

The system output provides the data needed to plan, predict and calculate periodic payments, and forecast the project duration. In the project planning phase, the system utilizes the knowledge depicted in the project definition phase to perform quantity take-off by calculating the quantity of each type of material. By applying the quantity take-off to the pay items and prices, the system calculates the item total price, price of each component or class of components, and the project price. Furthermore, like CPM, it calculates the project duration, the early and late start and finish times, and the allowable floats of each activity. Moreover, by relating activities to project specific components, the system calculates the price associated with each activity, and plots the price (i.e. cash-in) versus time relationship; i.e. the progress or S curve.

In the construction phase of the project, the system utilizes the reported progress of the project components at various construction stages to report the earned value, update the construction plan, and forecast the time needed to complete the project. Once the project status at a given time is defined, the system calculates the earned value of the different components, of activities, and of the project for payment request purposes. Such information provides a useful framework for project control by comparing planned with actual data. Further the system utilizes the reported status of the project components to infer the status of the activities that apply to those components and to forecast the time required to complete ongoing activities. The newly forecasted activity durations are then used to evaluate the remaining project duration. Other applications of this phase include geometric inspection of construction and follow-up of construction quantities. Thus, comparison of actual implemented 3-D construction coordinates (including areas, volumes, and distances) with the design drawings and the attributes stored in CAD is possible.

6 Conclusions

Usually project management phases are taken into consideration separately, which is of course time-consuming and inconvenient. The developed system combines all project management phases of project definition (design), planning, and construction using CAD, vision, and construction management systems which are combined through data-base structure. The system has a real-time potential to provide the data needed to estimate, plan, predict payments, and measure construction progress for payment and control purposes efficiently.

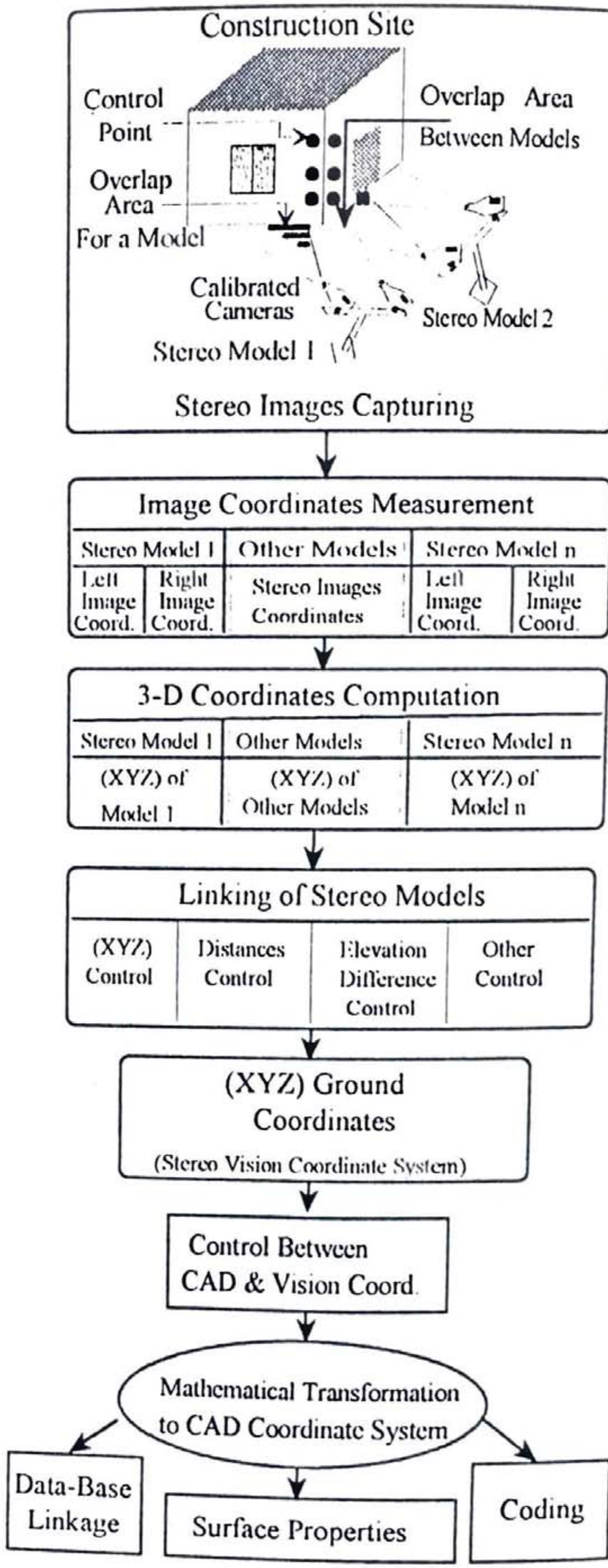

Figure 3 Construction phase scheme.

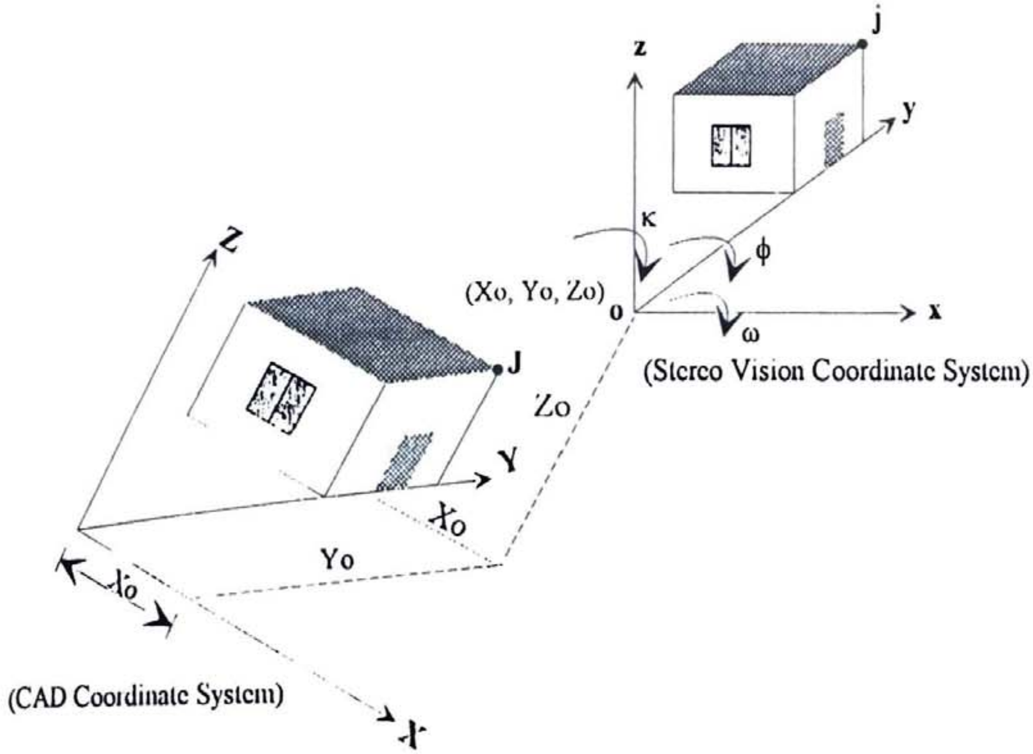

Figure 4: CAD and stereo vision coordinates transformation.

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