FRAMEWORK FOR AUTOMATED CONSTRUCTION PROGRESS MONITORING USING ROBOTIC VISION TECHNOLOGY

A thesis submitted in partial fulfillment of
the requirements for the degree of

Masters of Science
in
Construction Engineering and Management

by

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This is to certify that the
thesis titled

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has been accepted towards the partial fulfillment
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Dr. Muhammad Jamaluddin Thaheem
Supervisor,
Department of Construction Engineering and Management,
NIT, SCEE, National University of Sciences and Technology (NUST), Islamabad

DEDICATED

TO

MY PARENTS

&

MY WIFE AND MY SON

&

MCE & NIT

ACKNOWLEDGEMENTS

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I am indebted to my father for his support throughout the course of this thesis and painful proof reading of the draft. I am grateful to NUST for award of scholarship for completion of thesis.

ABSTRACT

Construction Progress monitoring is an activity of prime importance in the field of construction management. Liquidated damages, litigation and interim progress payments are dependent upon progress reports. Progress reports serve as a proof of client reliability and its ability to keep up to its commitments. Current construction progress reporting mechanisms are slow, labor intensive and have a lot of room for human error. Although progress reports are transmitted and stored digitally, their formation and updating is totally manual. The research presents an approach for automated construction progress monitoring using robotic vision techniques that have been successfully utilized in defense, health and entertainment sectors for a number of years.

The technique involves setting up and calibration of equipment, coordinating axes and adding images along with parametric information to the database. The code reads metric and non-metric progress using specific algorithm tailored for the purpose. The measured progress is stored as parametric information in the image which is saved in the form of an excel file. The obtained excel file can be used to update Microsoft Project and Primavera models that can create Gantt charts and perform PERT analysis.

The technique provides a low cost high tech solution to a real life problem that can be utilized by client who cannot visit sites due to security and logistical reasons and by small scale contractors who want to provide reliable updates to client in an automated manner.

The research provides insight into the use of cutting edge technology in adding value to construction industry and can be further customized according to individual needs of the end user.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

ASCE	American Society of Civil Engineers
BIM	Building Information Modeling
CCD	Charged Coupled Device
EXIF	Exchange Image file format
I/O	Input / Output
IEEE	Institute of Electrical and Electronics Engineers
OHS	Occupational Health & Safety
IPC	Interim Payment Certificate
MIT	Massachusetts Institute of Technology

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Construction progress measurement is an important measure that is necessary to gauge the probability of success of a project. Progress monitoring reports also serve as evidence in resolution of litigation claim as well as application of liquidated damages. Reliable construction progress monitoring mechanism needs to be in place on site at all times in order to ensure dissemination of correct information to all stakeholders. Construction automation is adaption of technology to digitize and automate construction processes. According to Azhar et al. (2010), “Building Information Modeling (BIM) is a the process of generating, storing, managing, exchanging, and sharing building information in an interoperable manner”. Thus information attained by automation of projects is stored in Building Information Models as parametric data. There has been growing interest in the construction industry to adopt BIM in the light of its various benefits of increased efficiency and resource saving during design, construction and operational stages. Implementation and benefits of BIM have not reached the developing countries because of high initial capital expenditure of implementation (CAPEX) and lack of knowledge of IT among construction professionals. This is resulting in wastage of millions of dollars of capital, poorer quality of constructions and greater accidents. It has been estimated that about 6-12% of construction cost is wasted because of rework due to defective work (Patterson & Ledbetter, 1989). Construction is vital from GDP and political perspective. However a close look at the construction practices presents an industry that belongs to 19^{th} Century instead of 21^{st} Century (Woudhuysen & Abley, 2004).

Figure 1.1 Decline in Construction Industry in Middle East (Esterin, 2009)

As shown in Figure 1.1 as well, Construction industry is facing a certain decline (Hansford, 2002) since the last decade due to poor economic growth, the collapse of investment banking in USA, Europe and Middle East. However, with revival of investment banking and economy, the construction industry is back on the path of recovery. In order to make best use of this recovery, construction industry should start to modernize itself and implement the latest cutting edge tools and technologies. In order to make this possible, it is imperative that the technology that brings such modernity should also be within reach of the industry professionals, especially in the low income countries of the South and South East Asia.

Due to the nature of their work and lack of requirement to modernize civil engineers are oblivious of the cutting edge technology and its importance in improving efficiency and productivity at work sites while contributing towards safety. The purpose behind choosing this topic was to provide a framework for the use of cutting edge cyber age technology into construction and provide a method that could benefit construction Industry.

1.2 Reasons for Selection of topic

Construction progress monitoring of building architectural elements is an important factor in lifecycle of a project that becomes basis of payments, litigation and liquidated damages. Construction progress needs to be communicated to stakeholders sitting far away from the site in different locations around the world. The construction progress is also a proof of contractor's reliability and his ability to deliver on his commitments.

1.3 Objectives

Objectives of this research are as follows

1. To develop algorithm for automatically measuring the dimensions of building architectural elements (walls, plastering, doors).
2. To measure progress of Architectural elements construction using the algorithm developed in step 1.
3. To provide output of progress in a usable format

1.4 Research Significance

Construction Progress monitoring is an important task in successful completion of a project (Dimitrov & Golparvar-Fard, 2014). Construction monitoring is usually done with the help of daily progress reports obtained by the contractor and requires great amount of paper work and human effort (Abeid et al., 2003), Figure 1.2 shows typical paper based construction progress report. It also requires owner to have trust in the subcontractors providing the progress report and thus an element of manipulation always exists since owner cannot be at all places at all times. It is assumed that site managers dedicate 30-40% of their time determining the actual progress of site (Son & Kim, 2010). All IPC are made on the basis of progress and therefore wrong reporting from the contractor can be a cause of significant financial loss.

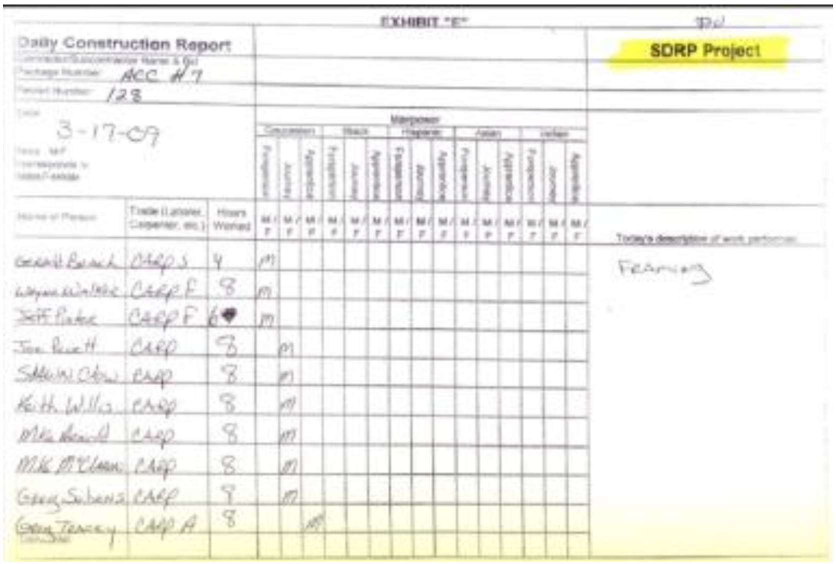


EXHIBIT "E"

Daily Construction Report

SDRP Project

ACC #7

123

3-17-09

Manpower

Today's description of work performed:

Framing

Figure 1.2 Paper based Construction Progress Reports (Roh et al., 2011)

Although progress might be represented and recorded on software like Primavera and MS Project, the progress is manually monitored and subsequently added to the system, thus the element of digitization does not exist in current construction management practices.

In the current AEC cost management hierarchy, the owner is usually represented by very few and high level resources. Therefore it makes it impossible for the client to verify progress. Using image processing and image based algorithms it becomes possible for client to review/monitor progress automatically by the use of images taken by subcontractors or contractors on site.

This research aims at providing an alternate to the conventional progress by the use of automation and developments in the field of computer vision which are being used in the defense industry for the last 30 years.

1.5 Cost Advantage

Current techniques of as built modeling involve use of laser scanners which are inherently expensive and computationally time consuming (Brilakis et al., 2011). While the research suggests use of photogrammetry which is cheaper and simpler solution to implement as compared to laser scanning. A laser scanner costs in the proximity of US$ 100,000 and requires specialized training and precautions to use. On the contrary, anyone can operate a camera without any special training or precautions. The maximum cost of a suitable DSLR camera is in the proximity of US$ 2,500. Cheap cell phone and Point and Shoot cameras can also be used, however, their accuracy decreases since high accuracy quality standards are not incorporated in the manufacturing processes.

1.6 Possible utilization of Robotic Vision

1.6.1 Utilizing BIM Parametric information and Image Data

Creation of BIM models requires a large amount of information that may come from engineering calculations, sketches, engineering and design information, studies and experiences. Based on the pool of information constraints are decided to be followed according to principles of semantics. Robotic vision can be value adding phenomenon during construction stage. Broadly it can be used to

1. Have a real time update on project progress.
2. Confirmation of project progress in 4D BIM Models.
3. Act as a tool to measure manpower that can be used as a real time input for 4D models.
4. Measure the presence of equipment on site for updating the real time BIM 4D model.
5. Measuring equipment productivity as a future input for BIM 4D Models forecast.
6. Create Real vs. Virtual hybrid models.
7. Deviation Detection.
8. Create As-built drawings.

1.6.2 Enrichment of BIM Parametric Information from Robotic Vision

Information from BIM Models can be correlated with information acquired through robotic vision algorithms therefore enriching the BIM models further. e.g.

1. Information on clear spacing of reinforcement can be extracted from models to validate compliance to specifications and a similar approach can be adopted for the codes as well. The same as-built information can be restored in the model.

2. Information on scheduled completion of milestones can be extracted from 4D BIM Models and combined with current progress obtained through Image processing to reevaluate project completion deadlines.
3. Machine learning and artificial intelligence algorithms and information attained from site progress can be used to predict project site progress and updating of BIM models.
4. Information of hazard locations can be stored in BIM and the same information can be used to control access to hazardous area.

1.7 Beneficiaries of the Research

The work done is beneficial to small contractors and owners who wish to have an automated framework for construction progress monitoring at a low cost. The complete setup would cost less than US$2000 if a DSLR camera is used and pictures are taken manually by a photographer. If a robot is used to acquire and transmit pictures, price of the setup might increase but the applicability would also increase for high end projects requiring more rigorous data collection.

1.8 Organization of Thesis

The thesis is divided into 5 chapters. The first chapter is about introduction followed by second chapter on literature review, third chapter on development and fourth chapter is on application of algorithm. The fifth chapter is about results and discussion.

CHAPTER 2

LITERATURE REVIEW

Most of the work done on construction progress monitoring through 3D vision techniques is related to laser scanners, which require very expensive equipment and high level of computation. Use of 3D laser scanner (LIDAR) has been suggested for automated tracking of progress (Nicolas et al., 2010). The authors suggested use of LIDAR combined with object recognition for creating 4D schedules. Based on the date of scan and object recognition, the 4D schedules are created. With the recent development in photography and availability of cheap DSLR camera and improved processing capacity of machines, the use of cameras is becoming more and more viable. Work has been done on progress monitoring through image processing for quite some time now.

2.1 PhotoNet II Software

PhotoNet II (Abeid et al., 2003) is a software developed to assist construction progress monitoring. It is an online tool used for remotely monitoring progress of the project with the use of cameras, video server, broad band connection and a computer with the software installed. The cameras placed at the strategic locations take time lapse images of site and upload it on the website through the video server. The videos are transmitted to PC through internet connection to be viewed and evaluated. Photo Net II has a Construction Progress Monitoring (CPM) engine as well. The user creates a project through the software and adds scheduling data to it. Afterwards the CPM engine creates the schedule and progress histogram which are dynamic. The big issue with the Photo Net II is the manual user input required to update the data. The only benefit it provides is the ability to remotely update schedule. But the user is required to manually skim through images and update the schedule consequently.

2.2 Interior Progress Monitoring with Augmented Reality

Cost Progress Monitoring research is based on indoor cost monitoring and works with color coding structural element according to their adherence to schedule (Roh et al., 2011). The process involves integration of real and virtual information. The algorithm has three major steps namely collection, analysis and integration, as detailed in **Error! Reference source not**

found.. The research uses a real time progress monitoring system and visualization tools to supplement the parametric information. The research approach involves use of an object oriented model with BIM to represent geometric information of construction objects as meaningful information using computer vision techniques.

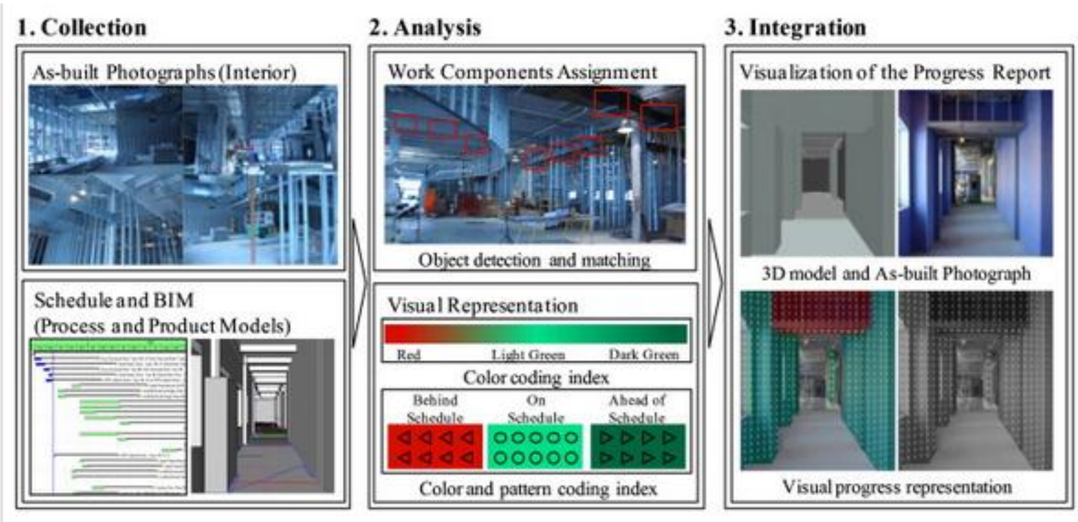


Figure 2.1 Process flow for integration of virtual and Real Images followed by Color Coding (Roh et al., 2011)

Figure 2.2 shows the framework for using BIM parametric information and safety codes to perform automatic code checking and suggest preventive and corrective action (Zhang et al., 2012). There is a machine learning algorithm that learns from the information available and suggests action based on learning. Camera can be integrated to the research to provide on-site safety update and raise alarm whenever there is a violation. This model requires modeling of safety elements in the BIM 3D representation.

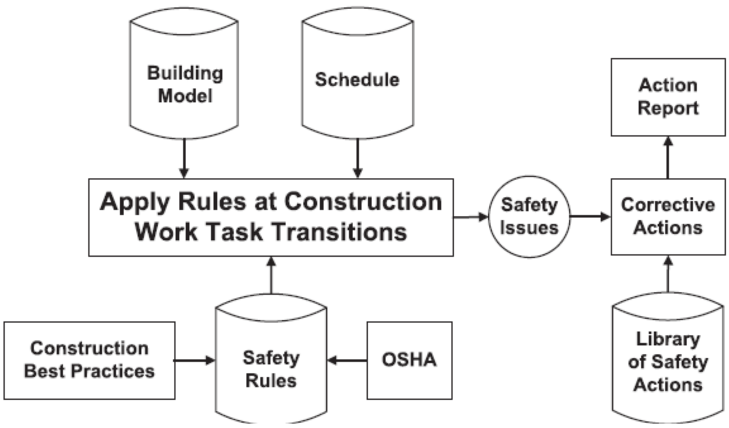


Figure 2. 2 Process flow for construction safety integration with Building information Model (Zhang et al., 2012)

In this research, the user contextual data is supposed to be manually fed, however a 4D model usually has this information. The object geometry and topology is extracted through IFC models and transformed into a form suitable for object recognition. The 3D representation is created using the OpenGL which is standard specification defining a cross platform API. The main concept in this research is object cost monitoring where objects are defined and each object can have certain classes which is an instance of the object.

The contextual data stored can be used to determine progress. A ray casting technique is suggested to be used. The algorithm also features a classifier that can classify a construction object from non-construction.

2.3 Color information for Progress Monitoring

Color information and 3D data use for structural element identification and subsequent progress monitoring is another approach suggested in literature (Son & Kim, 2010) . The paper suggests use of color photographs along with 3D ranging information obtained using bumble bee stereo imaging package, triclops and Matlab. The main idea is to use the color information that remains constant for a particular object as reference to identify object. But since the color information can vary considerably due to external factors such as illumination etc., the HSI index is used instead of RGB values, which is more stable in varying conditions. The technique is known as color thresholding where image is divided into various parts based on color of different objects. The threshold is decided after training on a set of data. The range of threshold should be decided in order to attain maximum pixels that belong to the object while having minimum pixels that do not belong to that object. The 3D range data combined with the segmentation from color thresholding provides a 3D model for the structure in construction. The 3D model is consequently compared with a model 3D structure created earlier in order to measure progress. Once the objects of interest are separated, 3D registration of pixels is done which is a complicated system but is simplified by the stereo vision system applied. The as-built model is then compared with built model in Matlab to measure progress as compared with actual structure. The experiment was done in the field as well and results attained were encouraging. However the experiment was applied only to structural steel member.

Vision methods have been used to track progress by identification and classification of materials and their textures (Dimitrov & Golparvar-Fard, 2014). This has two steps; training and classification. The change in color of concrete can help in tracking the number of days for which concrete has been poured. The algorithm proposed is based on statistical distribution of filter responses in the form of corners, spots and HSV values. The training set of images is converted to gray scale image and normalized with zero mean and 1 standard deviation. This is followed by application of Laplacian, Gaussian filters from the filter bank. For the classification of images the k-means clustering is used. In experiment it is observed that results are affected by the training data, image quality and image size.

2.4 3D Reconstruction by Videogrammetery

The creation of point cloud using videogrammetry has been tried (Brilakis et al., 2011). The process as mentioned in the paper dealing with reconstruction of buildings using videogrammetry, involves use of camera installed at a fix distance thus creating a stereo camera setup. The process involves installing cameras at specific locations and taking images.

This flow has been suggested by Prof Brilikas in his paper on 3D reconstruction using videogrammetry. The steps involved here include:

a. **Camera Calibration:** Camera has to be calibrated in order to determine its intrinsic and external parameters. There are total of 11 adjustments that have to be made. Calibration of intrinsic parameters is done on checkerboard.
b. **Feature Detection:** Second step involves detecting and matching features in the stereo images. A feature point detector and descriptor are employed.
c. **Structure and Motion Recovery:** This step recovers the 3D coordinates of the feature points and gives motion information between successive points. The structure of the scene is calculated through triangulation. Thus a sparse 3D point cloud is created for each pair of stereo frames. The camera estimates its own position using the iterative Closest Point Algorithm which is computationally expensive; therefore the framework has suggested a point tracking strategy using real time 2D trackers.
d. **Stereo Mapping:** The step explained above creates a discrete point cloud which may not be sufficient representation. A dense point cloud is created in this step using stereo frames. First epipolar geometry is created using two image planes followed by automatic discovery of each point in the second video corresponding to the first video. Since the query is only along the epipolar line, the computation is reduced significantly.
e. **Intelligent Smoothing:** in this step outliers are handled by using predefined random points. For each point a window is created with the point in the center and uniformity around the

point is checked. Non uniform windows are not processed since they usually contain corners.

Figure 2.3 shows implementation of aforementioned flow chart presented in the paper. As we can see that the point cloud is pretty clear representation of the original, but still there is a lot of noise and gaps that needs to be addressed.

Figure 2.3 3D Regeneration by Videogrammetery (Brilakis et al., 2011)

4D modeling has been tried with image processing (Kim et al., 2013). The flow chart is detailed in Figure 2.4. The application is a bridge project and involves use of various construction techniques. The research is very similar to what we are trying to achieve. The author uses HSV values to identify objects and 3D image mask to determine the stage of progress. The masks are generated on the basis of various stages of progress e.g. Mask 1 would show beam while Mask 2 would show interior columns, now the image taken would be matched with the masks and the stage of progress is measured by the component of the mask that matches the image. Thus a library of images is made that contains object oriented model where the image object contains schedule information as parameter. The as-planned schedule from a construction management program like Primavera, 3D BIM model and actual schedule attained from our image are exported to an excel sheet. The information is combined in Jetstream 4D modeling software to create and simulate a 4D model.

2.5 Monitoring by use of Photo log

Monitoring of construction performance using photograph log (Golparvar-fard et al., 2009) presents image processing based method for construction progress monitoring.

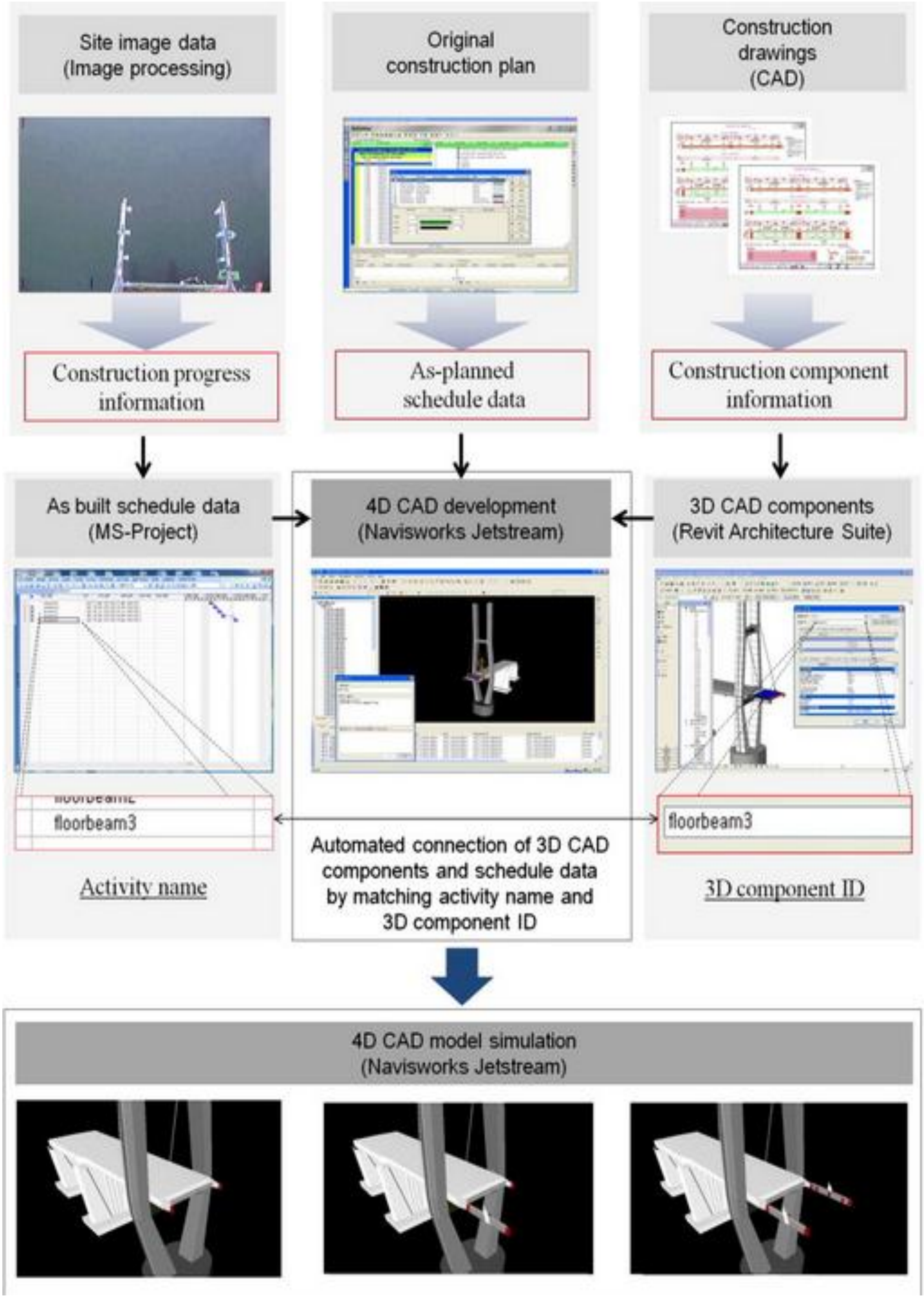


Figure 2.4 Automated Construction Progress Monitoring Framework

The author suggests use of photo logs and use of structure for motion algorithms to obtain 3D information from photograph logs. The author suggested a D^{4}AR model where progress discrepancies between as-built and As-planned model are measured through super imposition of 4D models over site photographs using different visualization techniques. The technique requires obtaining 3D information for images which was done using Structure for Motion technique, which involves obtaining images matching features across images and creating a set of ordered images. Following the feature detection and matching the 3D coordinates of the elements are measured, thus geometric information about objects is attained using the bundle adjustment algorithm (Triggs et al., 2000). This process is followed by 3D registration of the image information and the camera location. This information is overlaid with the already created as-planned model having all geospatial coordinates to create a D^4AR model. The overlaid as-built and as-planned information gives an insight into progress deviations and can also be used for progress monitoring.

CHAPTER 3

ELEMENTS OF ROBOTIC VISION SYSTEMS

The development of the code and system required acquisition of extensive knowledge of robotics, coding, geometric transformations and numerical methods to solve engineering problems involving multiple unknowns using least square estimation. The domain of robot vision and software is usually alien to civil engineers; however, survival of civil engineering as a profession is dependent upon utilization of modern day technologies.

3.1 Evaluation of Requirement

Computing and robot vision have found their application in various forms of construction engineering and management with the use of sensors, laser scanners, RFID systems and robots. The scope of implementation includes personnel monitoring, safety and quality assurance, facility management, environmental assurance, cost evaluation, remote monitoring, automated construction and construction progress monitoring.

Framework is developed for construction progress monitoring of architectural elements by implementation of robotic vision algorithms in order to provide a solution that would bring added value to construction management process.

3.2 Platform for development

There are various languages and platforms that can be used for coding and programming algorithms for robotic vision. These include C++, C#, JAVA and python etc. The choice of language for coding is dependent upon the ease of use, availability and cost of acquisition of platform for running the language as well as the acquaintance and experience of the researcher. Usually high level languages are preferred because of ease of use

Figure 3.1 provides comparison of various platforms that could have been utilized for coding of the algorithm. However as visible from the reference, Matlab appeared to be the most suitable choice for development of code.

Table 3.1 Benefits-Dis Benefits of different software platforms with respect to problem at hand

	C++	Matlab	Java
Benefits	1. Available image processing libraries. 2. Fast processing for complex algorithms	1. Easy to use interface 2. Built in Image Processing and Vision Functions Toolbox. 3. Built in mathematical functions.	1. Does not require compiler, since it runs on JVM. 2. No cost of compiler or software.
Disbenefits	Coding is more difficult as compared to Matlab	Slow processing of loops	Built for easier application and therefore not suitable for complex tasks like image processing

3.3 Matlab

Matlab is high level language and visual environment for visual computing. Matlab being extremely efficient while dealing with matrices is the perfect platform for all vision related applications. It has a number of toolbox that assist in image acquisition, processing and vision related functions.

3.4 Matlab Computer Vision Toolbox

Matlab computer vision toolbox is developed for vision related applications providing functions that are able to perform most of complex mathematical and numerical operations like computation of epipolar lines, fundamental matrix, essential matrix and sparse 3D reconstruction using image correspondence. Although knowledge of mathematical relations and concepts behind these functions is necessary for efficient utilization of the toolbox, the requirement for coding each and every function separately has been offset, therefore saving a huge amount that would have been spent debugging and exception handling.

3.5 Development of Algorithm

Algorithm for automated construction progress monitoring of architectural elements requires acquisition of knowledge related to photogrammetery, image acquisition, image processing, computer vision and coding. After deciding on platform to be used for coding, the algorithm was developed for knowledge area separately and afterwards all parts of algorithm were combined into one algorithm. Each step of algorithm development is discussed separately.

3.6 Image Acquisition

Image in passive devices like cameras is done by incident light on the CCD sensor. The CCD sensors store the impression on the array in a digitized format.

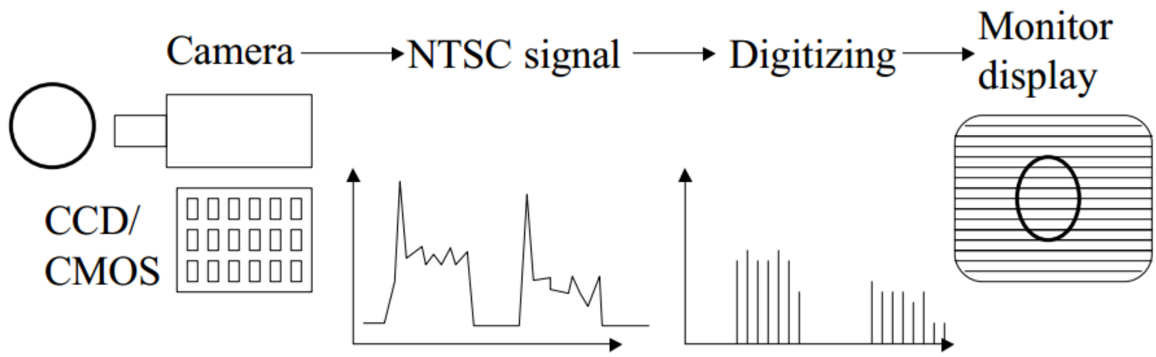


Figure 3.1 Image Acquisition Process Flow (Gonzales & Woods, 2008)

Previously the image was formed on camera film which had chemicals having property to absorb light and retain the impression. However the modern DSLR cameras digitize and store information by following a process shown in Figure 3.1

3.7 Central Projection Model

The camera acquisition follows a perspective project model of pin hole camera where image of Point A is projected on image plane as a point ‘a’. There are two Cartesian coordinate systems for central perspective projection. Figure 3.2 shows the camera central projection model. One belongs to the image plane and is 2 D with a fixed z-axis at a distance –c from the image and the other is the world coordinate system.

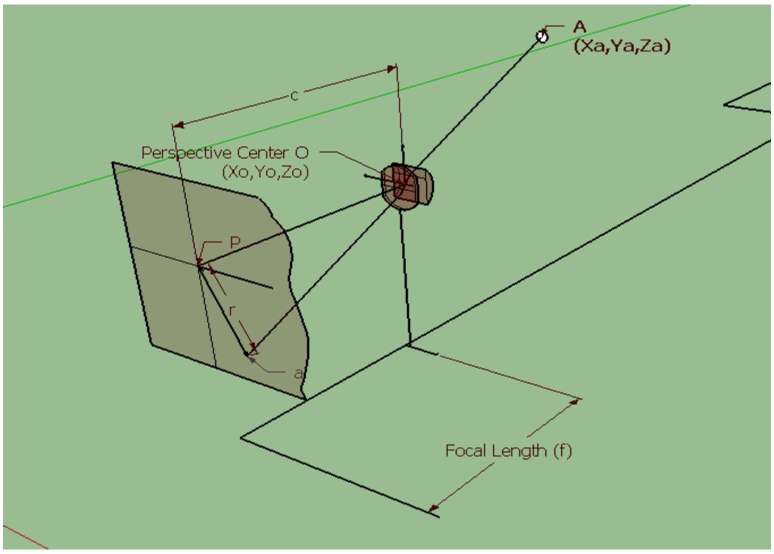


Figure 3.2 Camera Projection Model showing Perspective centre, principal point and principal axis

The Point O is the center of projection and the perpendicular from image plane to the center of projection and is called the Principal axis. The point at which the principal axis intersects the image plane is called the Principal Point. The transformation from 2D image coordinates to 3D world coordinates requires multiple images to be taken. The point 'a' on image plane would change its location based on the orientation of the camera.

The computation of exact camera parameters requires camera calibration that will be explained in section 3.8.

3.8 Camera Parameters Determination

Camera parameters include external and internal parameters of the camera. Camera parameters can be assumed based on (Exchangable Image File Format) EXIF data of the camera and can be calculated using grid method. Image acquisition based on assumed parameters instead of calculated parameters creates issues during the processing and computation part of the algorithm. The camera calibration process provides information on the basis of focal length and translation values. The camera calibration matrix is given by the relation in Eq 3.1.

$$C_k = \begin{matrix} f_{dx} & 0 & t_{dx} \\ 0 & f_{dy} & t_{dy} \\ 0 & 0 & 1 \end{matrix} \qquad \text{Eq 3.1}$$

Where $f; Focal\ Length\ of\ Camera\ expressed\ in\ terms\ of\ No.of\ Pixels$

t_x, t_y; *Location of principal point expressed interms of pixel values.*;

Camera Internal matrix computation requires image acquisition of a grid from different angles and determination of important points on a grid. This is followed by measurement of key spaces between grids along with their angles. The measured information is compared with actual distance between grid elements and error of camera measurement is determined. Various techniques exist for camera calibration that includes Roger Tsai, Linear algebra method (Fryer, 2001) as well as use of vanishing points. Camera calibration effect is worse for cheap camera Point and Shoot cameras as compared to better quality DSLR camera systems. Cameras distort images by scaling skew and distortion as shown in Figure 3.3.

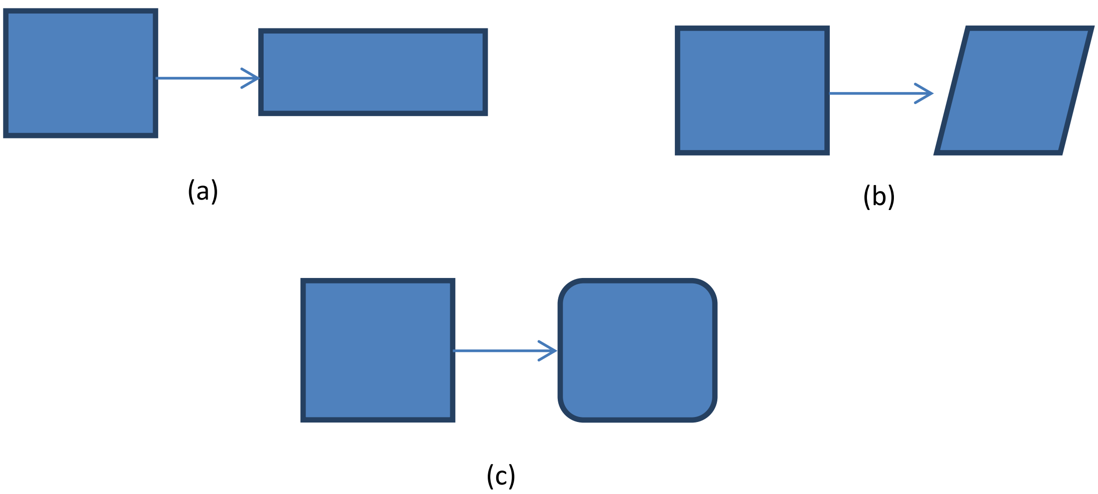


Figure 3.3 Camera Distortions, (a) Scaling Distortion, (b) Skew (c) Lens Distortion (Duraiswami, 2000)

3.8.1 Camera Calibration Experiment

For camera calibration multiple software are commercially available. These include photomodeler scanner package, camera calibration toolkit and camera calibrator in the Matlab calibration toolbox. Photomodeler used a proprietary grid for single and multi calibration while calibration toolkit and Matlab calibrator use a checkerboard pattern. Figure 3.4 shows multi sheet calibration technique that is an alternate to checkerboard calibration method.

Images are taken in landscape mode and portrait mode by rotating camera by 180°. The aperture and focus setting should not be disturbed at the time of image acquisition.

Figure 3.4 Calibration Grid Setup using Multi sheet Calibration for Photomodeler

3.8.2 Calibration using Photomodeler

In order to perform calibration using photomodeler software, image of the calibration grid is taken from all sides and using multiple orientation of the camera. The images are then loaded into the software and the calibration is run using the calibration dialog. Photomodeler reads all images, extracts grid information from them and performs measurements of distances and angles. Afterwards the process is performed and output containing information related to the camera calibration parameters and residual error is provided as an output. The error should be less than 1 pixel in order to be acceptable. The error can be further reduced by modifying the target detection points by making them closer to the actual points.

Figure 3.5 shows image taken from Photomodeler ® software for single grid calibration. The subject figure also shows the magnified residuals.

3.8.3 Calibration using Camera Calibration Toolkit

Camera calibration toolkit (Bouguet, 2013)uses grid pattern for camera calibration. The entire code of the calibration toolbox is written in Matlab using ‘calib_gui’ command in Matlab. At least 15 images of the grid should be taken and uploaded on the camera calibration toolkit console. The images are then individually read and corners are marked on them. Afterwards

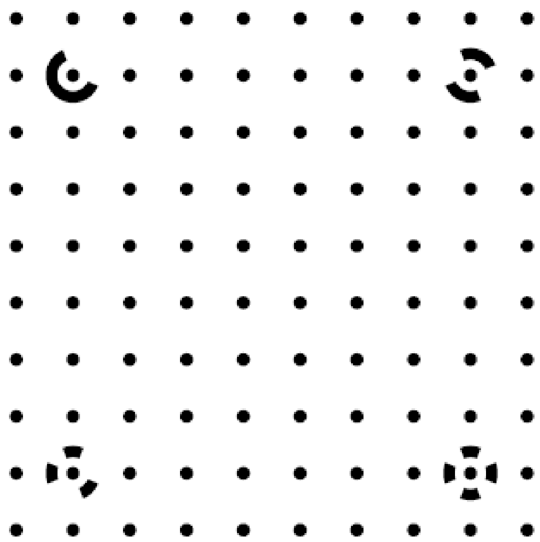


Figure 3.5 Photomodeler Proprietary reference grid.

Matlab finds the corners of the boxes and, based on the width of box provided in mm, the code provides the camera calibration parameters.. The factors for radial and tangential distortion are also provided by the program,

Figure 3.6 Selection of Images taken from Photomodeler® interface.

This toolbox also provides the camera external parameters if specifically required. In order to compute the externals only, one image is required for one camera. The image is loaded to the toolbox and corners location along with box dimensions is provided as a seed point. The camera external matrix world coordinate system origin is in accordance with the layout shown in Figure 3.7.

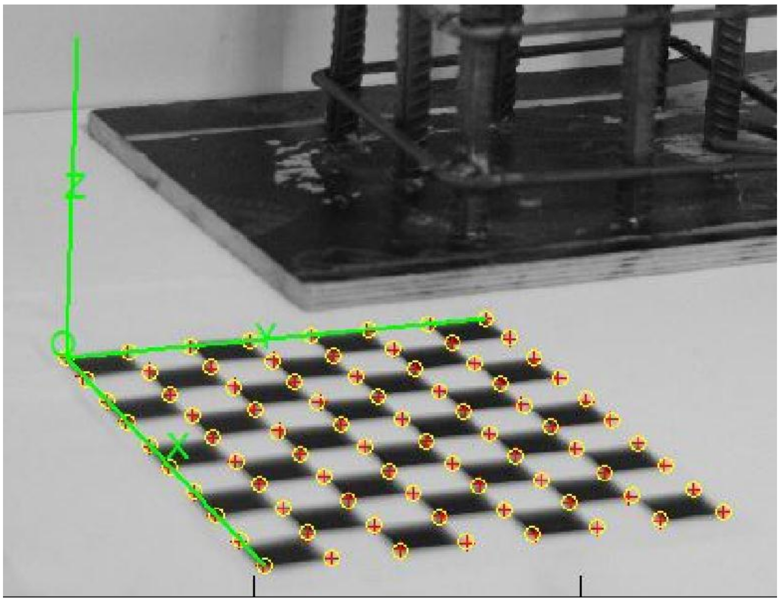


Figure 3.7 World Coordinate system with reference to Checkboard

Matlab calibrator function has been added in the computer vision toolbox of Matlab v8.3. The technique is very similar to the camera calibration toolbox mentioned earlier, however, there is more automation and less requirement of giving seed points. The calibration grid for camera calibration toolbox is asymmetric and therefore creates coordinate axis according to Figure 3.7

The accuracy of all the calibration tools is very similar to eachother however the user interface differs greatly. The choice of the tool is dependent upon the availability and user preference. While the matlab calibrator and the toolbox are available Free of Cost, photomodeler is paid software. Agisoft®(AgiSoft, 2014) has also created a calibration tool that is similar to Photomodeler in its application. AgiSoft Lens can also be downloaded free of cost from the internet.

3.9 Coordinate System

Coordinate transformation is key to the algorithm developed in this research. There are two types of coordinates system in the spatial domain as shown in Figure 3.8

1. ***World Space***
2. ***Model Spaces***

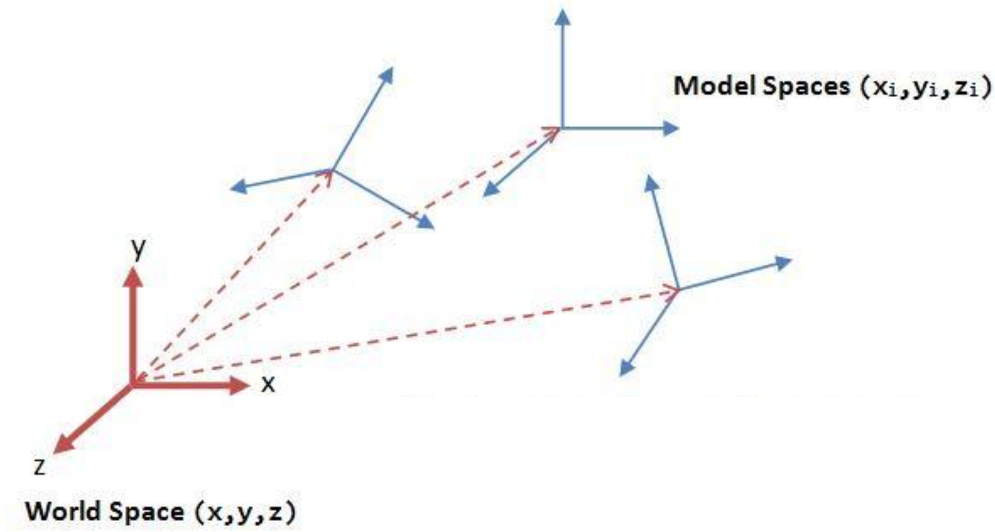


Figure 3.8 World Space Vs Model Spaces

3.10 3D Point Transformation

A 3D point in space is represented by its x,y,z components and is represented by a homogeneous vector given by Eq 3.1

$$\boldsymbol{P_i} = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \qquad \textbf{Eq 3.1}$$

3D points from Model to world coordinate system is done by transformation matrix given by the translation matrix which has a rotation and translation component. If rotation component is given by R and translation component t then transformation is given by the relation in equation Eq 3.2

$$[\boldsymbol{R}|\boldsymbol{t}] \qquad \textbf{Eq 3.2}$$

The above given equation is 3x4 matrix which gives transformation from one coordinate system to the other coordinate system. Therefore the transformation from x, y, z which are our Model coordinate system, to X, Y, Z which represent the world coordinate system is given by the relation in Eq 3.3

$$\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & c & t_x \\ d & e & f & t_y \\ f & g & h & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \qquad \textbf{Eq 3.3}$$

Where a to h are the transformation parameters which are actually trigonometric functions based on the rotation along *x, y, z* with respect to X, Y, Z. The homogeneous coordinates are used due to additive nature of the coordinates.

The coordinates and transformation will form the basis of our algorithm and will be used to identify spatial location of the construction progress.

3.11 Image in a Digital Form;

Images acquired using process mentioned in section 3.6 consists of pixel with each having discrete intensity values attained by a process of quantization and sampling. Image can be stated as a function $I(x,y)$, where I represents the intensity values and x and y are the spatial coordinates. In the equation form the relation can be written as Eq 3.4

$$\boldsymbol{Image} = \boldsymbol{I}(\boldsymbol{x}, \boldsymbol{y}) \qquad \textbf{Eq 3.4}$$

As shown in Figure 3.9, Image therefore can be defined over a rectangle with a finite range. The origin of the coordinate’s axis for image plane is located on the top left corner of the image.

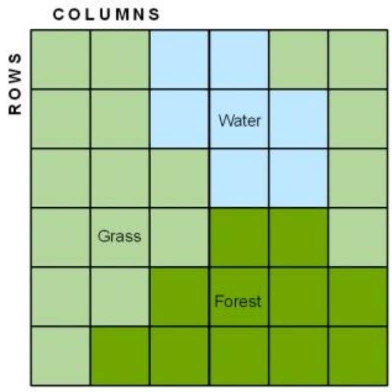


Figure 3.9 Raster Image representation of Image Plane for standard Image (Briggler, 2012)

3.11.1 Sampling of Images

Sampling is the process of discretization of image space that can be represented by transformation of continuous signal to a discrete signal. Sampling divides the image area into finite number of pixel values as shown in Figure 3.10.

3.11.2 Quantization of Images

Quantization is the process of quantifying a range of values into a single value using a technique such as Lossy compression. The quantization of color values makes it possible to store images in different devices. Discrete Cosine Transform (DCT) and Discrete Wavelet Transform (DWT) are a few of the quantization techniques that result in JPEG and JPEG2000 images respectively.

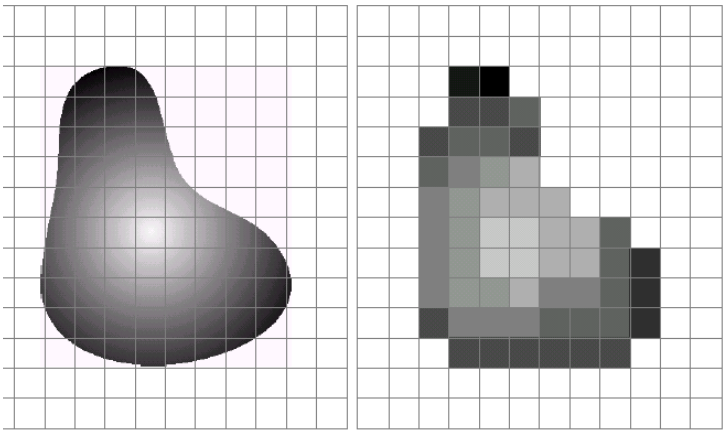


Figure 3.10 Image Sampling and Quantization (Gonzales & Woods, 2008)

3.12 Processing of Images

Image processing is an operation performed on an image to create a new image. Since image is basically an array it can be modified by additive and subtractive operations. Image processing provides methods for enhancing images and highlighting certain features for future processing. The result of image processing is an image.

$$g(x,y) = t\big(f(x,y)\big) \qquad \text{Eq 3.5}$$

In Eq 3.5 a transform t is applied to the image f in order to obtain a transformed image g.

3.13 Blurring and Edge Detection

Blurring is an image processing process that tends to smooth out image by removing noise from it. Blurring operations makes corners less visible. Blurring operation can be applied by a mask that can either be weighted or non-weighted. Figure 3.11 shows the blurring mask. Mathematically blurring operations can be given by the equation

$$g(x,y) = \frac{\sum_{s=-a}^{a}\sum_{t=-b}^{b} w(s,t) f(x+s, y+t)}{\sum_{s=-a}^{a}\sum_{t=-b}^{b} w(s,t)} \qquad \text{Eq 3.6}$$

$\frac{1}{9} \times$

1	1	1
1	1	1
1	1	1

$\frac{1}{16} \times$

1	2	1
2	4	2
1	2	1

Figure 3.11 Non Weighted (Left) and Weighted (Right) Blurring Mask

Blurring can be performed using Matlab 'imfilter' syntax. Another technique for blurring is to keep the object out of focus during the imaging operation which provides result similar to application of masks; however accuracy cannot be controlled in such cases. Figure 3.12 shows the application of blurring mask on a wall element.

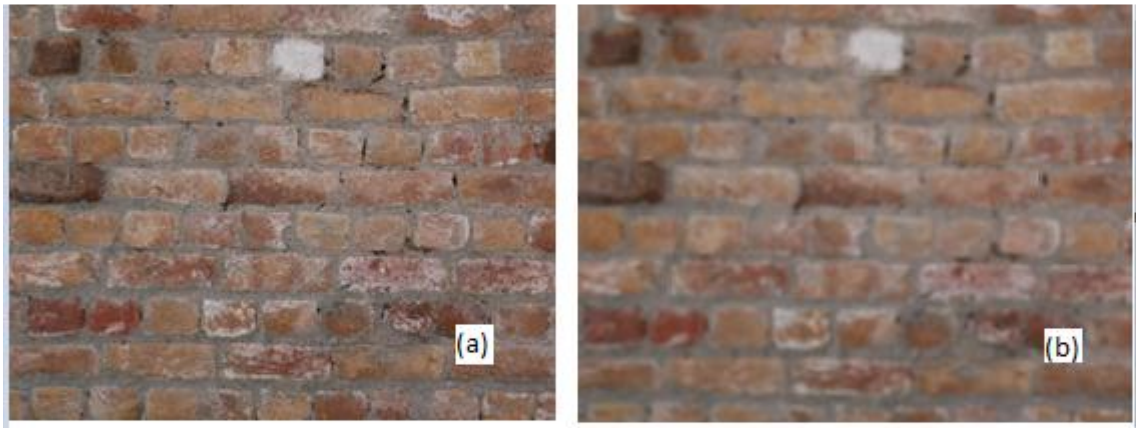


Figure 3.12 (a) Image before averaging Operation (b) Image After Averaging Operation

3.13.1 Detection of Corners

Corners are detected by applying partial derivative operation to the images, where change in intensity is measured by taking partial derivative along each direction. The relation for detection of corners can be given by the Eq 3.7.

$$\nabla f = \begin{bmatrix} G_x \\ G_y \end{bmatrix} = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \end{bmatrix} \quad \text{Eq 3.7}$$

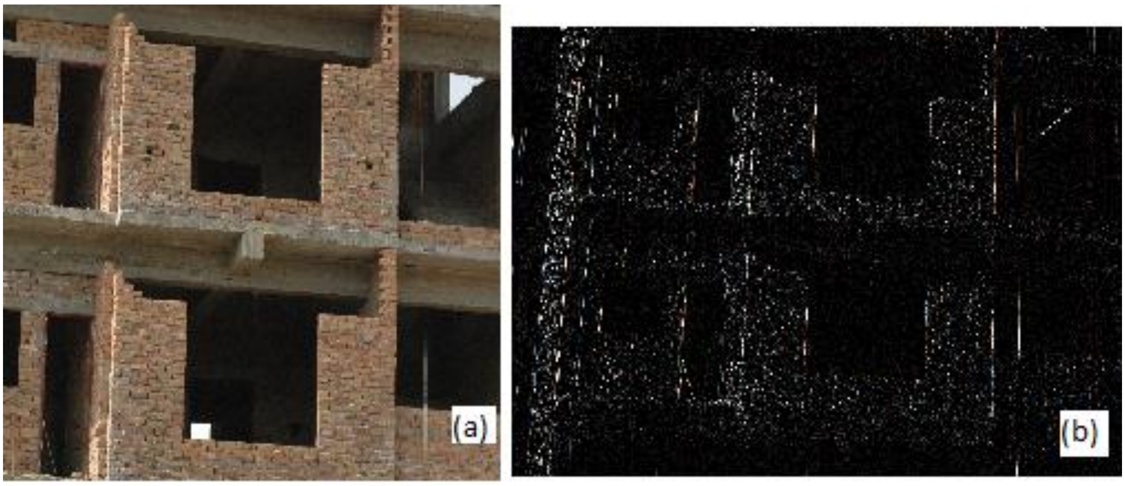
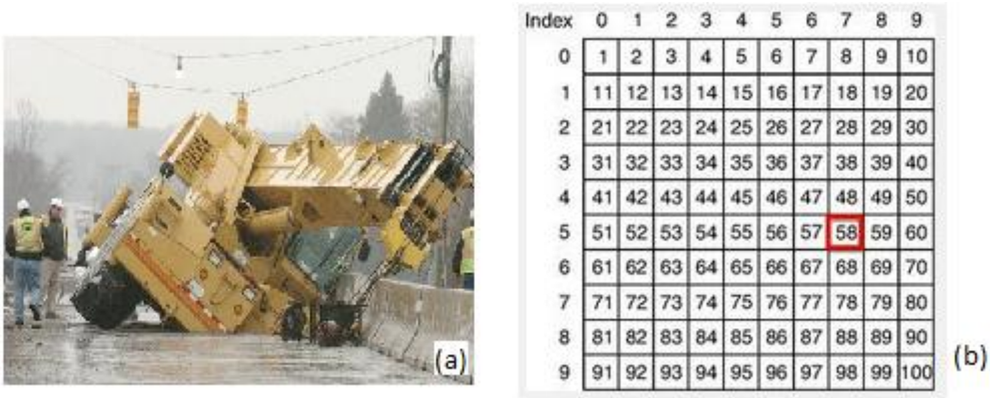


Figure 3.13 Image (a) before application of edge detection, (b) after application of edge detection

Corners are important elements in an image and are required whenever there is a need to identify objects in the image. The process is also known as image segmentation.

3.14 Robotic Vision

Robotic vision is the process of extracting information from images; it differs from processing of image since here the output is information and not an image. Robotic vision is the process giving computers the ability to extract information from the array of numbers stored in the form of image, giving human like perception. Figure 3.14 shows a representation of perception of humans and arrays on computers.



Index	0	1	2	3	4	5	6	7	8	9
0	1	2	3	4	5	6	7	8	9	10
1	11	12	13	14	15	16	17	18	19	20
2	21	22	23	24	25	26	27	28	29	30
3	31	32	33	34	35	36	37	38	39	40
4	41	42	43	44	45	46	47	48	49	50
5	51	52	53	54	55	56	57	58	59	60
6	61	62	63	64	65	66	67	68	69	70
7	71	72	73	74	75	76	77	78	79	80
8	81	82	83	84	85	86	87	88	89	90
9	91	92	93	94	95	96	97	98	99	100

Figure 3.14 What humans see (a) vs What computer sees (b) (Pierini, 2009)

Computer vision involves complex numerical and probabilistic techniques in order to extract information from images. This technique was developed initially for defense related applications and has currently found application in science, engineering and technology etc.

3.15 Stereo

Stereo is the technique used for obtaining depth information from images which contain 2D information only (Hartley & Zisserman, 2004). Images are taken from different positions and depending upon disparity the depth information is extracted. Stereo has found application in robots and construction of 3D information from 2D images. The basic model for 3D imaging can be seen in figure Figure 3.15.

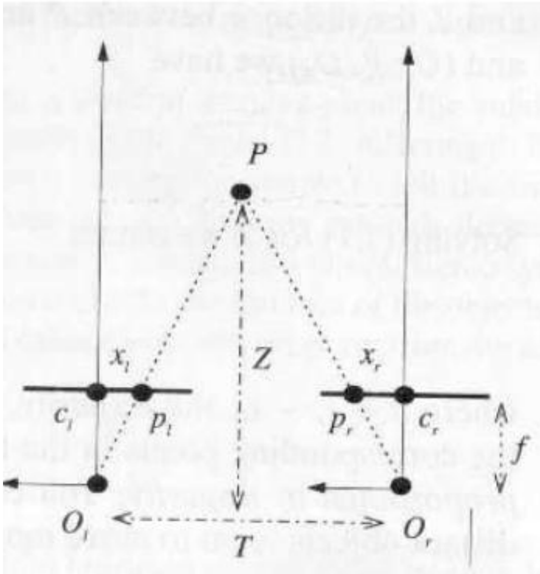


Figure 3.15 Stereo Imaging System Model(Cardenas-Garcia, Yao, & Zheng, 1995)

In Figure 3.15, 'T' is the distance between imaging equipment, Z is the depth information, f is the focal length and P is the object we are trying to measure the distance. The P is projected as p_r and p_l on left and right camera with center $O_l$and O_r. The depth information is written by Eq 3.8.

$$Z = Tf/d \quad \text{Eq 3.8}$$

$$d;\ disparity\ between\ pixels\ measured\ on\ images.$$

Using the stereo vision technique, Model coordinates of important image points are extracted, identified and registered.

3.16 Procedure for Measurement

Measurement is done for metric and non-metric progress using time lapse image taken at different intervals. The computation details are explained in detail in Chapter 4.

3.16.1 Procedure for Metric Progress Measurement

3.16.1.1 Image Acquisition at t=0

Image will be taken of the structural element at t=0 from various angles. Images must contain complete height information of the wall and should not be taken from wide angles such that detail between images gets obscured. Figure 3.16 and Figure 3.17 show representation of wall element and camera stations during image acquisition. The time and grid reference are noted at the time of image acquisition.

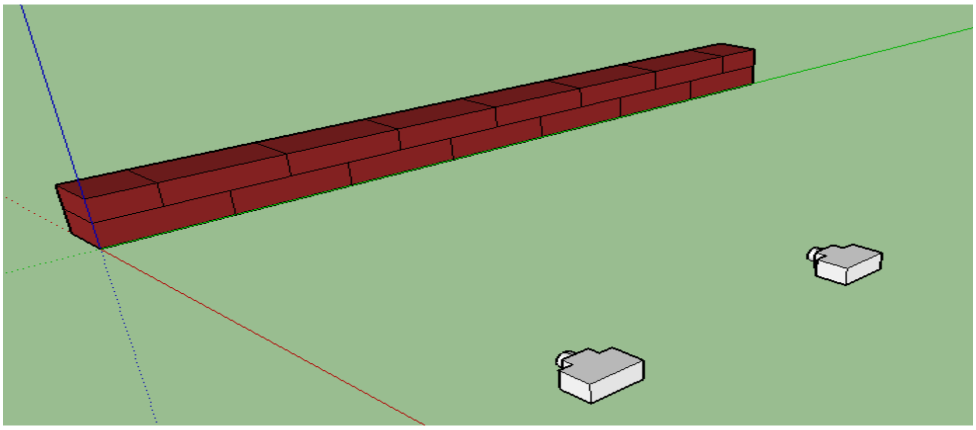


Figure 3.16 Test Specimen with Camera Stations

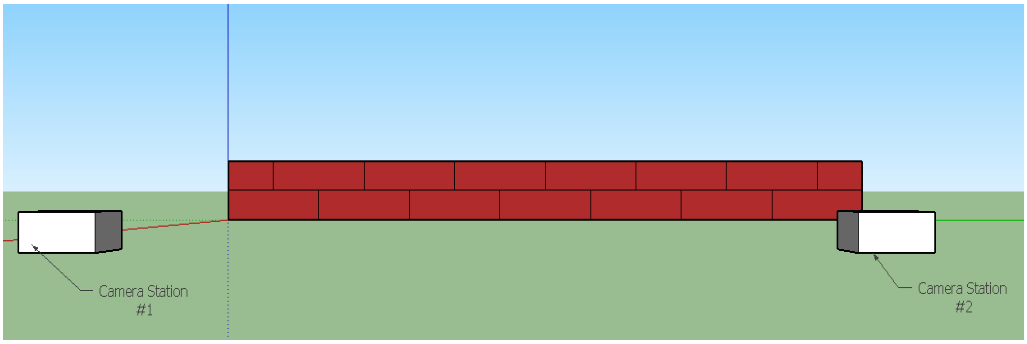


Figure 3.17 Test Specimen with Camera Stations

3.16.1.2 Image Acquisition at time t=T

After a lapse of time T, some layer of wall would be built. The grey color in figure 3.18 represent the progress made after first image that was shown in Figure 3.17. The image are taken keeping in view the consideration mentioned earlier and time alongwith grid reference are recorded.

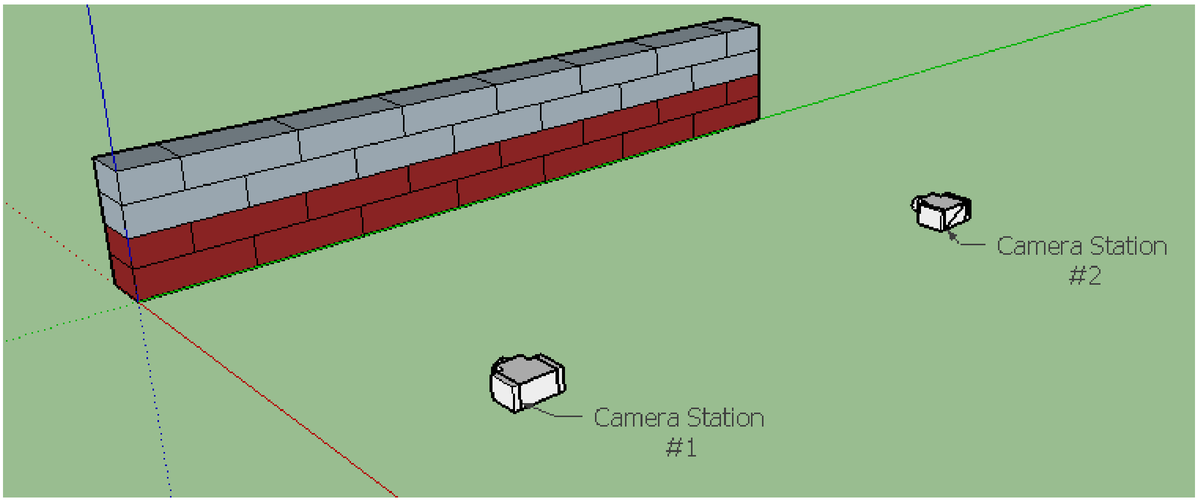


Figure 3.18 Test Specimen at time t=T

3.16.1.3 Execution of Code

Using both images in algorithm acquired above, the change in height and progress in the wall is measured using the algorithm explained in Chapter 4 in detail.

3.16.2 Measurement of Progress changed by Coating on Surface

Non-metric progress is not a function of any physical measurement rather it is characterized by the change in appearance of the object. In order to measure progress of completion of plastering over a wall, image would be taken after finishing of the wall and before plastering process. The following steps would be followed

Image acquisition will be done after completion of masonry work on the wall and no further increase in height is planned. Figure 3.19 represent imaging operation before plaster is applied.

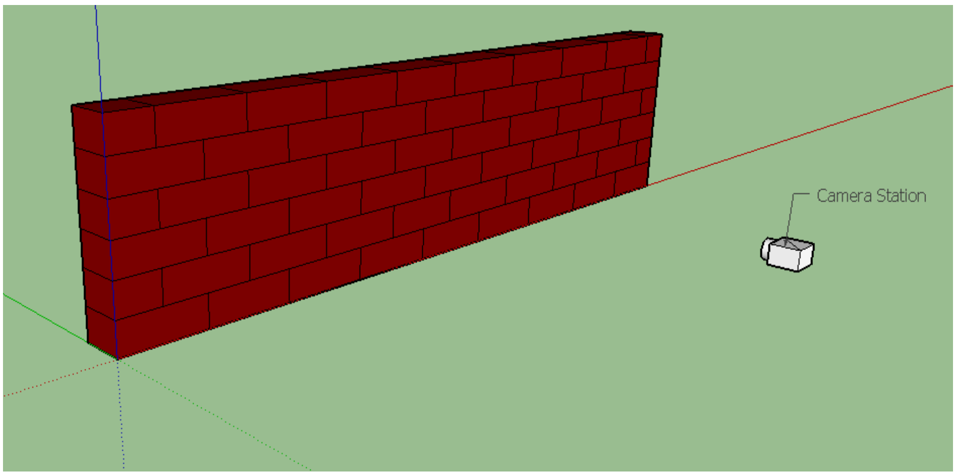


Figure 3.19 Image before plastering operation has been performed

Image acquisition is again performed after completion of plastering activity on the wall. Only single image is required for non-metric progress measurement. Figure 3.20 is a representation of image acquisition after plastering activity has been concluded. The progress will be determined by the identification of color information.

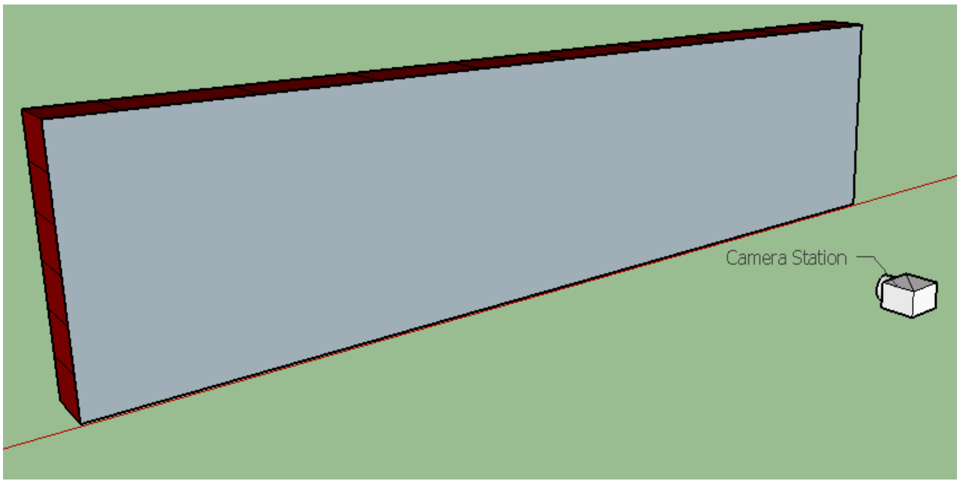


Figure 3.20 Imaging after Plastering operation has been performed

3.16.3 Measurement of Progress Achieved by Addition of Elements

The addition of elements to the wall is also a measure of progress. Addition of doors and windows elements can be confirmed by taking images before and after installation of doors and windows by following steps similar to those mentioned in Section 3.16.1. Please refer to Figure 3.21 and Figure 3.22 for representation of imaging before and after installation of doors.

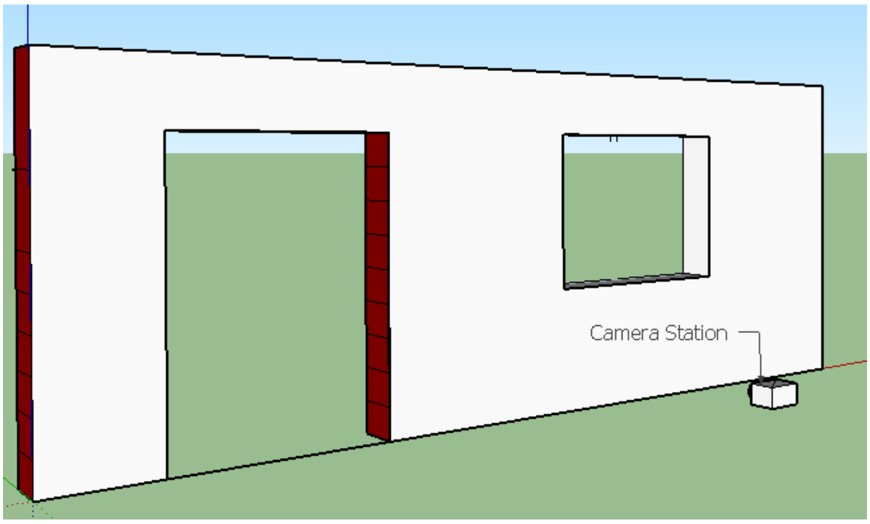


Figure 3.21 Imaging before installation of doors and windows

Figure 3.22 Imaging After installation of doors and windows

CHAPTER 4

AUTOMATIC ARCHITECTURAL ELEMENTS PROGRESS MONITORING SYSTEM AND APPLICATION

The developed system is based on a number of Model coordinate systems and one world coordinates system. The information from Model coordinates is extracted and transformed into world coordinate system. All information is stored in an object oriented model of images which contains information about location, time of image capture, type of information extracted.

The backbone of algorithm is a storage database and object oriented model for the images. Broadly algorithm is divided into 4 parts given in flowchart in Figure 4.1.

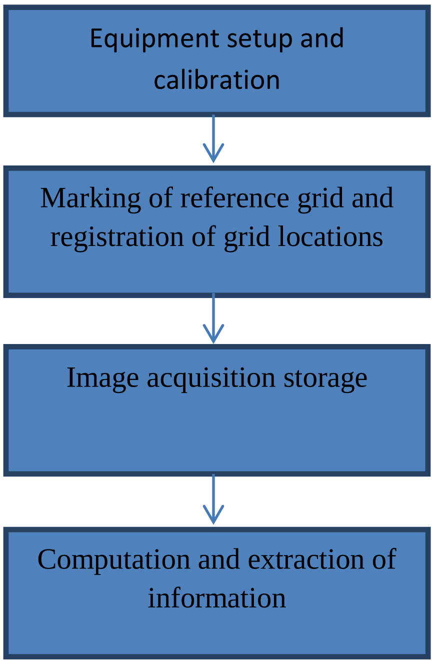


Figure 4.1 Process Flow Summary

The algorithm requires manual input for computation of height information and determination of type of progress. It is imperative to ensure care in camera calibration and careful placement of all reference marks. The imaging equipment should be of optimum quality since low cost Point and Shoot equipment induces noise and errors making inputs unreliable.

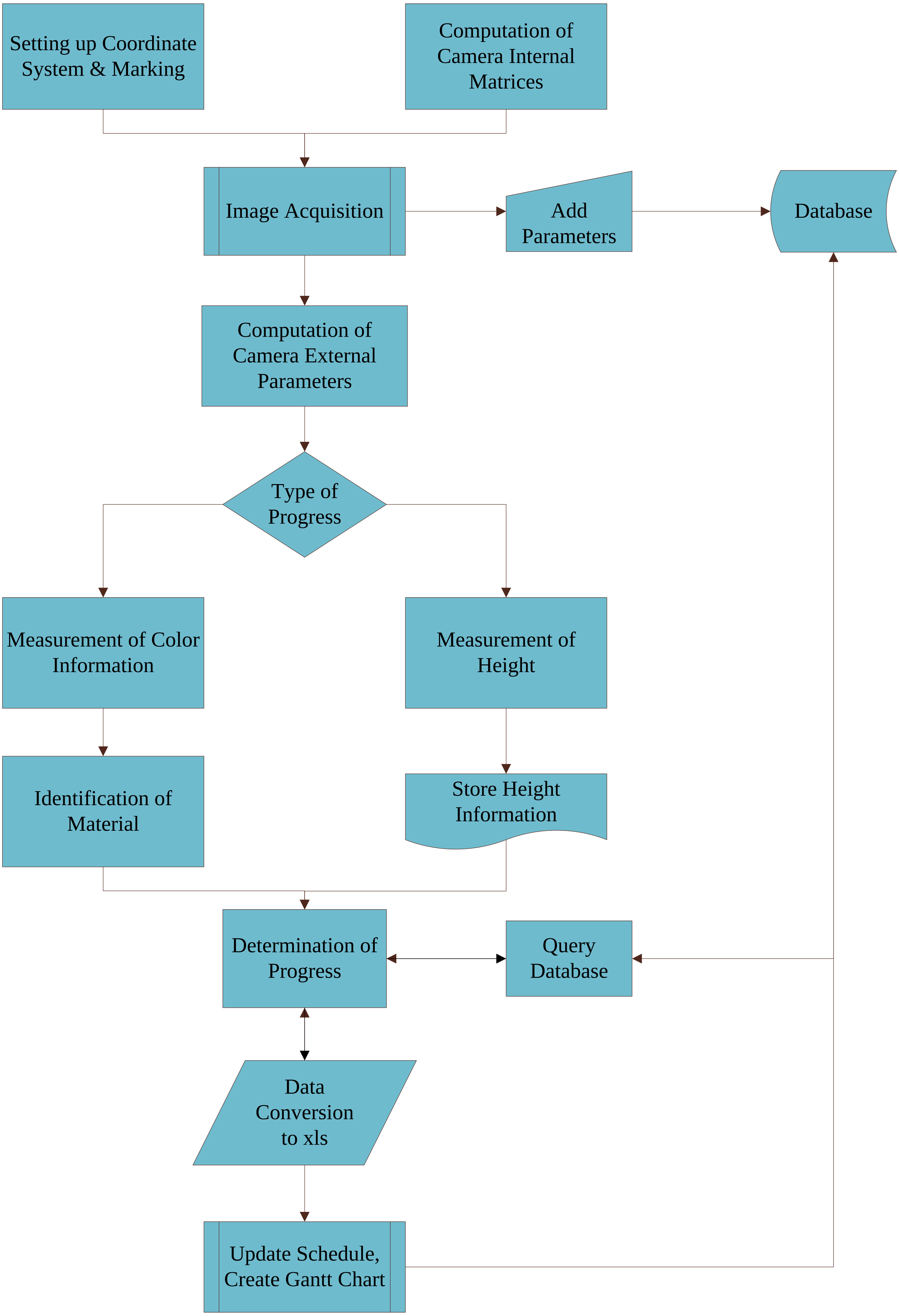


Figure 4.2 Algorithm

4.1 Steps for implementation of process

4.1.1 Calibration of camera

Camera calibration was done using the Matlab camera calibrator. The Matlab camera calibrator provides a simple and easy to use interface for camera calibration. The images are loaded into the calibration toolbox and then uploaded to the toolbox. Figure 4.3 provides screen shot of calibration images uploaded to system.

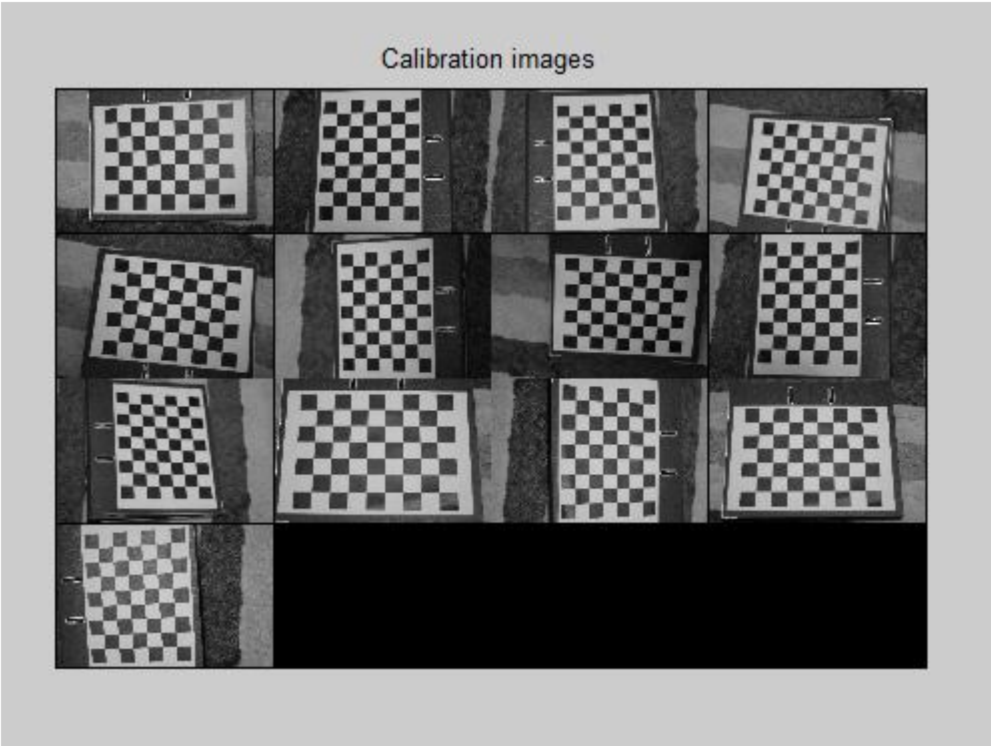


Figure 4.3 Camera Calibration Images

After adding the images, calibration is run using the camera calibrator GUI, shown in Figure 4.4

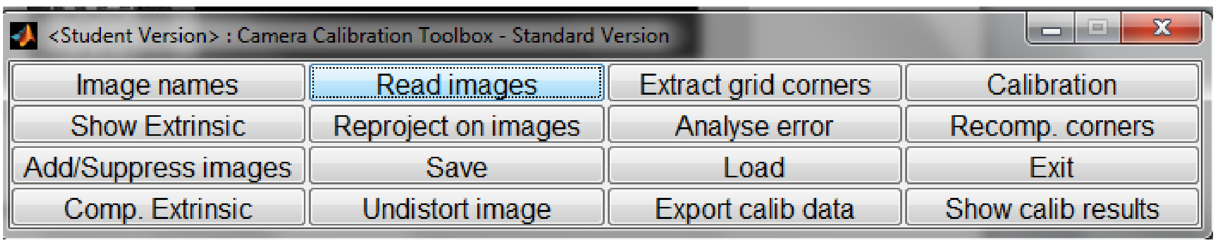


Figure 4.4; Camera Calibration Toolbox GUI

This step is followed by extraction of image corners and provision of size of each square in the grid. The extracted corners and grid is displayed on image for review as shown in Figure 4.5.

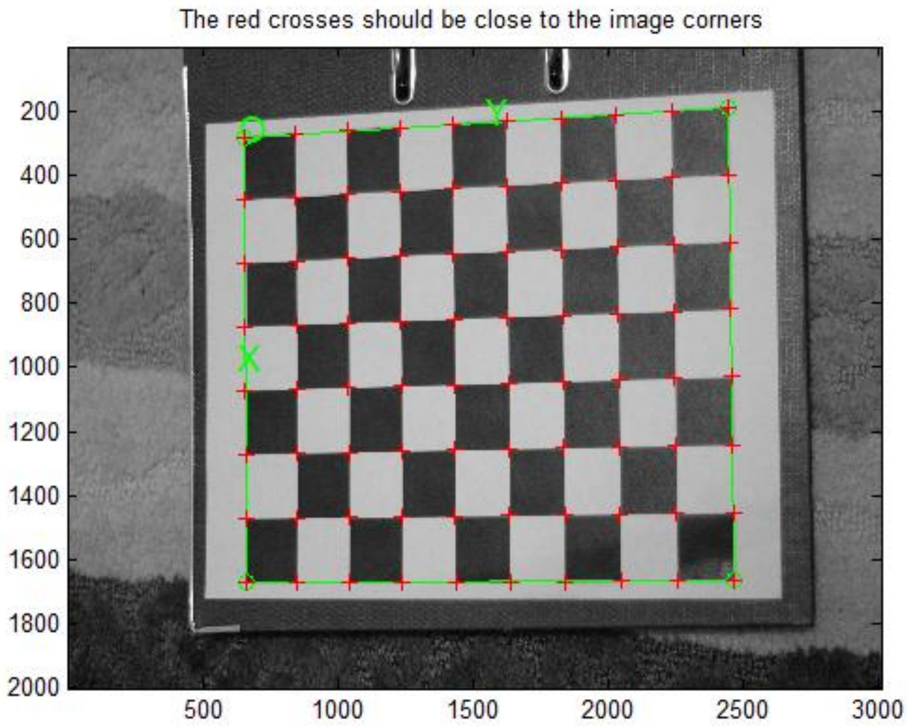


Figure 4.5 Detected corners on a calibration grid.

The toolbox reads all images and extracts corners according to the input. This step is followed by an iterative calibration algorithm that reads images, extracts corners from them and then compares the results with the actual information about grid present in the memory. The calibration results are displayed as an output given below:

```
Focal Length:          fc = [ 7181.69884   7184.58810 ] ± [ 114.60105   115.89654 ]
Principal point:       cc = [ 1413.60666   826.84620 ] ± [ 84.60473   87.58094 ]
```

In order to check accuracy of the calibration, the camera location during imaging can be seen using the 'show externals tab' on calibration tool box. Figure 4.6 gives camera external locations. The error of calibration should not be more than 1 pixel. Pictures can be adjusted in-order to reduce the pixel error.

The calibration values are in terms of pixels. The lens used for the acquisition of images was a 50mm lens and calibration gives the value as approximately 7180 pixels. The principal point on the 3000 x 2008 pixel camera does not lie in the center and has an offset as seen in the calibration values.

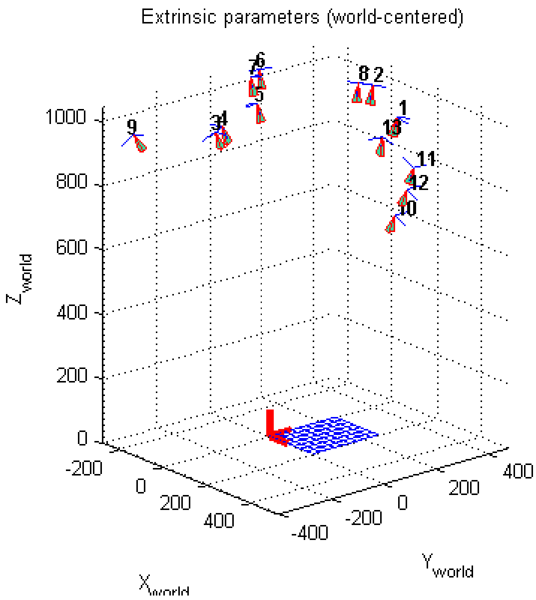


Figure 4.6 Camera External Locations

4.2 Setting Up Coordinate System

The marking of reference of world and Model coordinates is done for spatial referencing in the building as shown in Figure 4.7. The world reference point should be marked outside at a prominent location and should not be moved during the entire duration of the project. All other reference grids will be marked according to the world coordinates system.

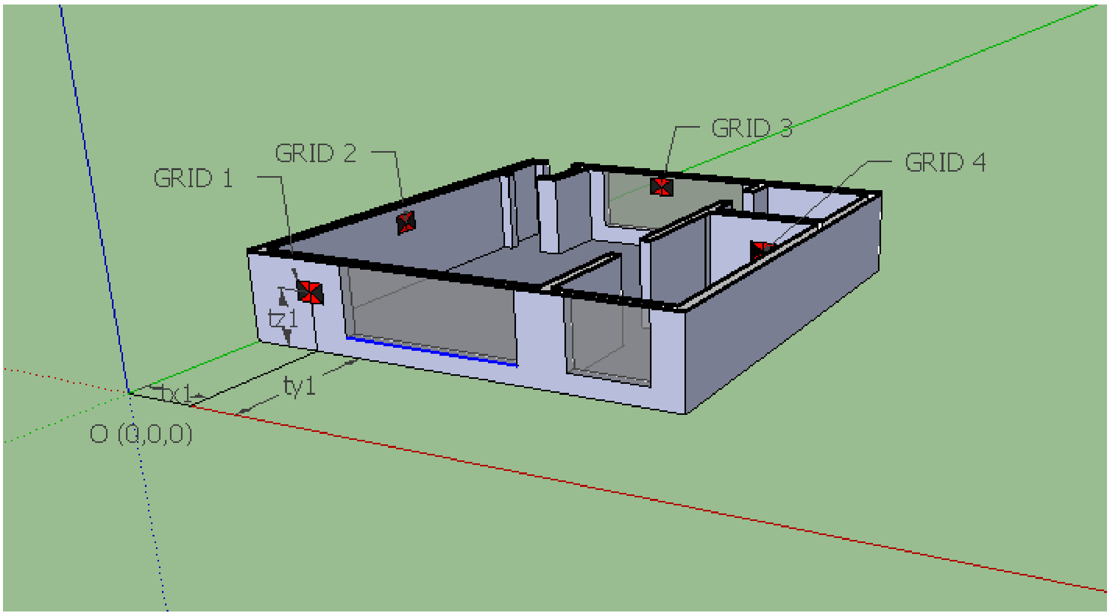


Figure 4.7 Layout of world origin and reference grids

In order to simplify the problem, grids are not rotated throughout the structure and only translated; therefore, the transformation matrix from Model grid coordinates to world grid coordinate is given by relation in Eq 4.1

$$\boldsymbol{P_G} = [\boldsymbol{I}|\boldsymbol{t}] * \boldsymbol{P_{li}} \qquad \textbf{Eq 4.1}$$

Where I is the identity matrix and $P_G$is the points location in world coordinate system and P_{li} are coordinates according to Model coordinates system reference by Grid (*i*). Expanding Eq 4.1 we get the relation for coordinates transformation from Model Grid (i) coordinate system to world coordinate system as

$$\begin{bmatrix} X_G \\ Y_G \\ Z_G \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} X_{li} \\ Y_{li} \\ Z_{li} \\ 1 \end{bmatrix}$$

The parameters of every grid are stored in the Grid object created in Matlab. In our experiment there were four grids and the translation and rotation of their origin is stored.

The 'gridInput.m' function takes values and translation/rotation coordinates of grids and stores them in Grid (i) structure. The prompt that appears to add grid translation coordinates is shown in Figure 4.8.

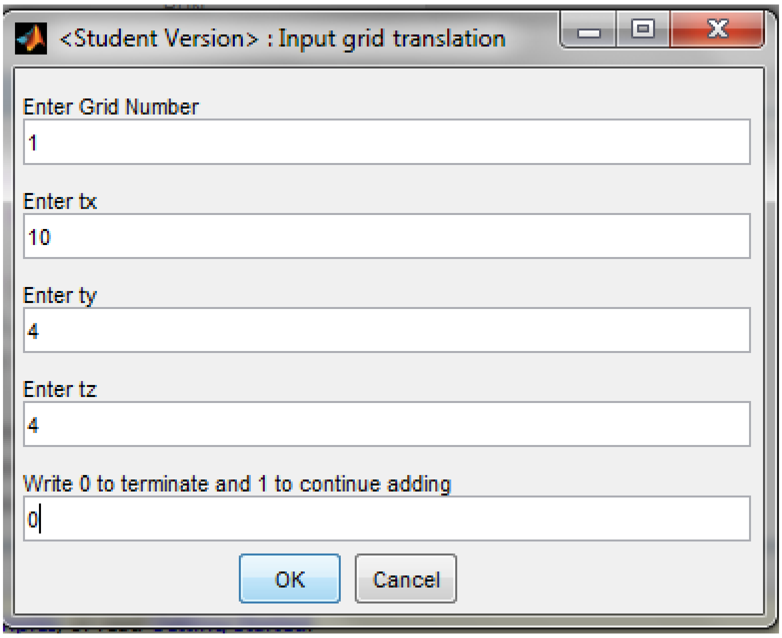


Figure 4.8 Prompt to add grid translation coordinates

Once grid locations are added to the database next step is acquisition of images and their storages.

4.3 Acquiring Images

Image acquisition is a continuous process and would take place throughout the life of the project. Acquired images are stored in the database in an object oriented form where each image will have the following parameters

a. Date image was taken
b. Location of Image Grid
c. Last activity detected from schedule
d. Current activity expected from schedule

4.4 Measurement of Progress

Measurement of progress is separate for Metric and Non-metric progress as shown in Figure 4.9

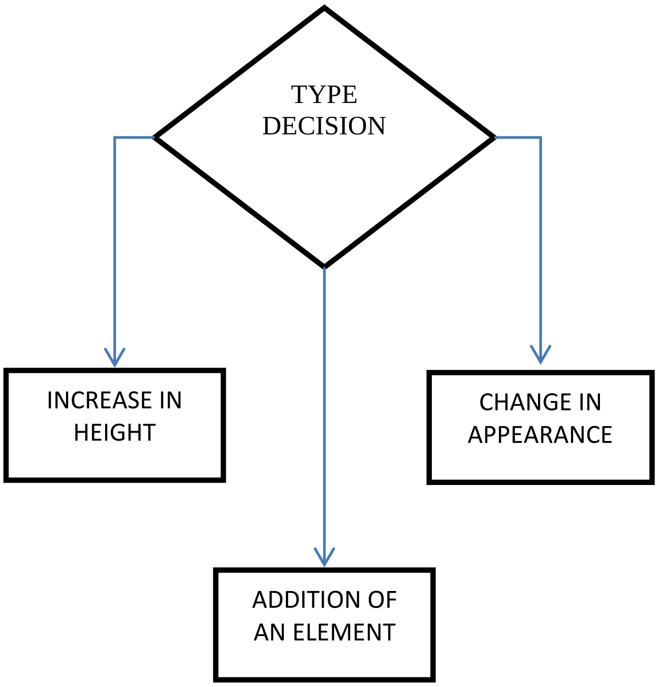


Figure 4.9 Summary Flow Chart for Type of Progress Measurement Decision

4.4.1 Measurement of Height

In order to measure height of the image, the grid must be present at the time image is being taken and camera calibration should be done. measureHeight.m code is run in order to measure the height. The grid measures camera externals and is stored in the image. The checkerboard is read by the image and external matrix computation is done giving the rotation and translation of camera with respect to the Model coordinate system shown in Figure 4.10. Once externals are calculated, the pair of images is read and the base of the wall is manually marked on both walls followed by manual marking of the top of wall on both images. Using stereo triangulation, the code computes the base and top coordinates of the walls and the difference in the Y component of the base and the top is the height of wall.

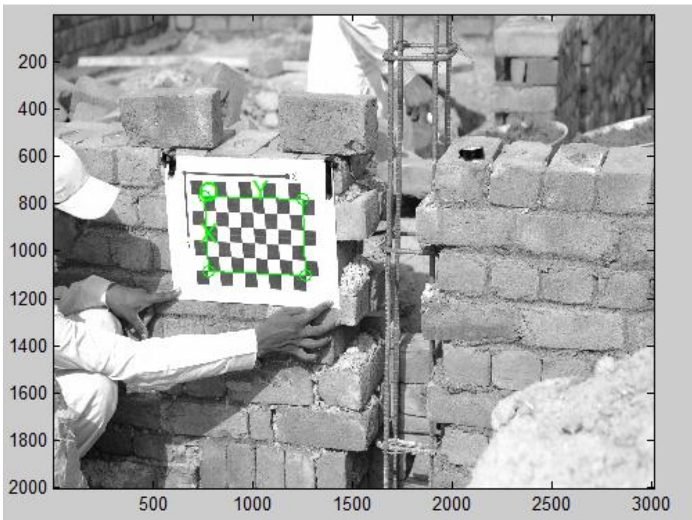


Figure 4.10 Marked Reference coordinate System on Checkerboard

The difference in x component gives the height of the wall. In the above case height of wall is given by

$$Ht = x_{T\_}x_B$$

$$Ht = 461 - (-85) = 546mm$$

4.5 Measurement of Non Metric Progress

Measurement of non metric progress e.g. plastering on brick is measured by judging the change in color of the wall. Since RGB color values tend to vary with the display adapter and illumination a lot, therefore HSI index is used for thresholding, According to training data the plot for saturation values of brick and cement plaster are as shown in Figure 4.11 and Figure 4.12.

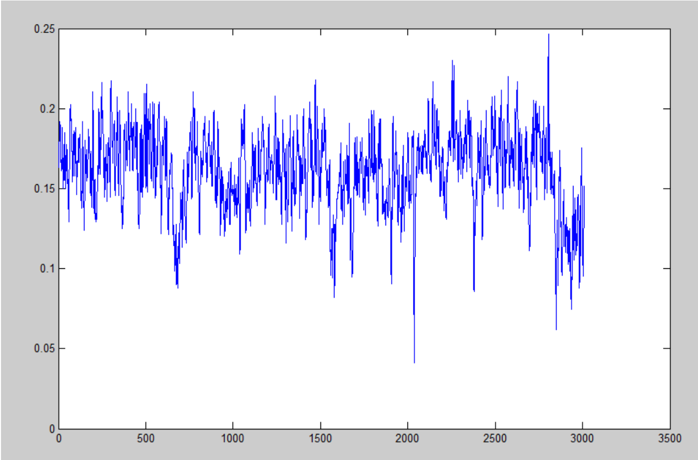


Figure 4.11 Saturation Index Plot for Plastered Wall

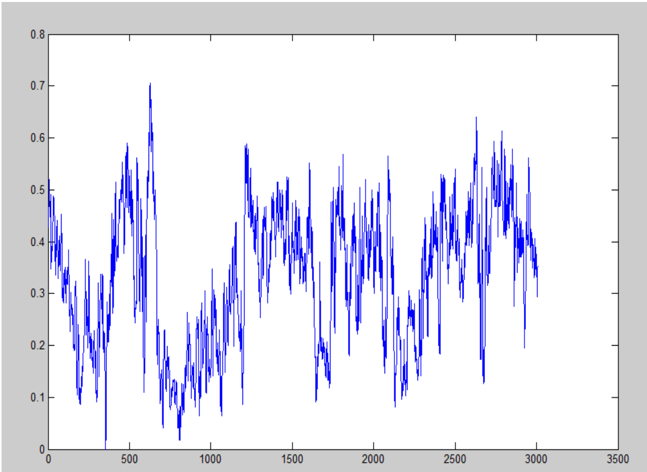


Figure 4.12 Saturation Index Plot for Brick Wall

According to the training data, the Saturation Index for brick wall and cement plaster can be given by the following relation

$$.3 < Brick\ Saturation < .5$$

$$.15 < Cement\ Saturation < .2$$

We measure the saturation index of the image taken at t=10 and t=15 and according to saturation index measure their values. Then according to following pseudo code the progress is measured

If Material at t=10 is Brick

{

If Material at t=15 is Brick

Result no Progress

Else if Material at t=15 is Cement Plaster

{

Update Schedule at t=15 days duration

}

}

End

The brick saturation images at t=0 and plaster at t=T taken at site are shown in Figure 4.13. Using the saturation values the change in material is detected and progress is noted.

Figure 4.13 Saturation Image vs Original of Brick and Cement Plaster

4.6 Measurement of Addition of element

Addition of elements can be measured by taking the image of an object before and after addition from the same location. Afterwards the difference image is computed between the image t=0 and t=T in order to determine addition of elements. The thresholding values discussed in previous section can be used to determine the kind of element added to the structure. Figure 4.14 shows steps in involves in determining the addition of door element.

Figure 4.14 (a) Wall image at T=10, (b)Wall image at T=15 (c) Blurred Difference (d) Binary Door Location

The images at t=0 and t=T are blurred in order to remove noise by using average filter, thus getting rid of brick corners and unnecessary information. This step is followed by conversion of image to binary form in order to highlight the door presence.

The plot in Figure 4.15 shows the pixel coordinates of door location extracted from a row strip of the image. The plot is not for complete length of the image and the last 100 pixels are omitted to remove edge abnormalities

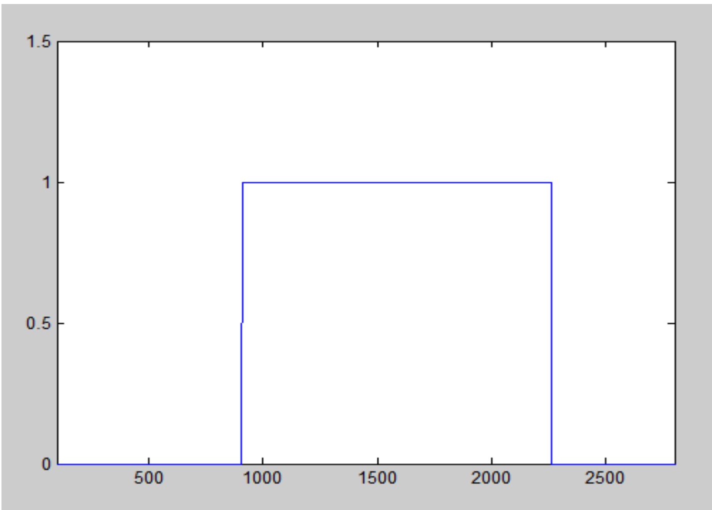


Figure 4.15 Plot showing location of door

4.7 Displaying Information

The extracted information is displayed and output is given in excel format. The information is updated for every image taken. The information extracted is in the format shown in Table 4.1

Table 4.1 Output of Progress Sheet

Grid Reference	Image Name	Activity Type	Activity Start	Activity End	Duration	Change	Next Activity
A	DSC_8147	Wall	10	15	5	400mm	Metric'
A	DSC_8148	Plaster	15	16	1	Color	Non Metric'
A	DSC_8149	Door	16	17	1	Addition	Non Metric'

The elements of the table include the following information.

4.7.1 Grid Reference

Grid reference gives the grid at which progress is being measured. The grid would contain information of the location and therefore spatial progress registration is based on grid reference.

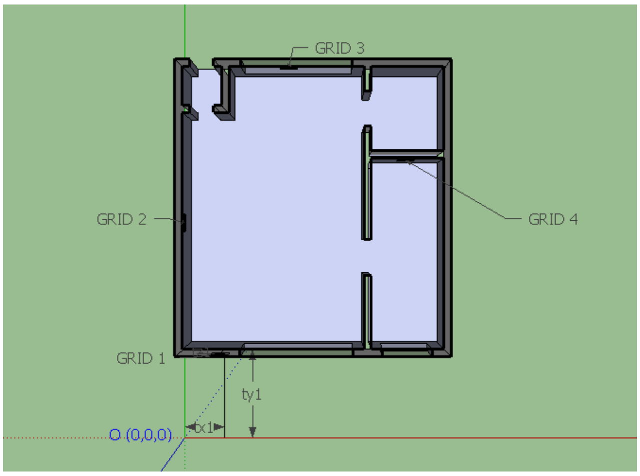


Figure 4.16 Grid Locations for Progress Measurement

4.7.2 Image Names

Gives the information about images used to measure progress for physical check in the later stages

4.7.3 Activity Type

Activity type gives information about the type of activity whether it is wall construction, plastering or addition of doors or windows.

4.7.4 Activity Start Date-End Date

Activity start date- end date information is extracted from image object oriented model to give dates of progress.

4.7.5 Change

Change column gives information about the change from previous activity. If the change is metric, the column gives change in height in mm. If the change is non-metric the column gives the type of change whether it was change in color or addition of element.

4.7.6 Next Activity

The next activity column provides information about the type of activity that would come up next. The activity information is used as a parameter to measure the progress for next activity.

4.7.7 Duration

This column gives the duration in number of days and reflects the number of days taken to complete the project.

CONCLUSIONS AND DISCUSSIONS

5.1 Discussions

The Algorithm has been tested for different cases in different conditions and the resulting accuracy is ±5 cm which is acceptable considering the fact that height of building elements usually exceeds 100 cm in height. The accuracy is dependent upon the calibration of camera and the setup. There are different parameters that affect the accuracy of the measurements.

5.1.1 Effect of Lighting

Lighting affects the aperture settings of camera as well as F-stop setting. Too bright or too dim lighting tends to effect the color detection through saturation part of the algorithm while making it difficult to identify corners of the grid. Figure 5.1 and Figure 5.2 represent very bright and dark lighting conditions.

Figure 5.1 Imaging in Bright Setting with 1/1000 sec Aperture Time.

Figure 5.2 Imaging in Poor Lighting Conditions

Figure 5.1 shows image taken in bright light where the grid corners have become blurred making it difficult to compute externals based on grid location, while Figure 5.2 shows example of image taken in poor lighting conditions.

5.1.2 Scaling of the Image

With the increase in scale of image the error also increases, since the pixels per mm index reduce and an error of one pixel tends to translate more in metric terms. As the scale increases, the distance from grid also increases making the external parameter calculation inaccurate. Image taken from 1m to 3m depth tends to give best results.

Figure 5.3 Imaging Done from a Distance greater than 4m.

Figure 5.3 represents imaging done from a distance greater than 4 m. As observed in the image, the black squares in grid are too small and, therefore, it would be difficult to accurately detect their corners and perform external parameters calibration.

5.1.3 Working Space

Cramped working spaces make it difficult to perform imaging from correct angles. This issue is more pronounced when imaging is performed indoors.

5.1.4 Grid Location and Focusing

Grid should be located towards the centre instead of the corners to offset the effect of radial distortion. Gird should be focused and corners should not be blurred. The line of sight between grid and imaging equipment should not be hindered by the presence of external object. The focus of imaging equipment should not be altered during imaging of one grid element.

5.2 Important considerations during experiment

During the experiment, following considerations should be kept in mind

a) Images should be taken in similar lighting conditions.

b) Camera stations should not be changed during the course of experiment.

c) No measure should be taken that could affect camera calibration.

d) The background should not be changed during the course of experiment.

5.3 Review of Research Objectives

The purpose of research to create and implement the algorithm has been fulfilled. The algorithm has been run on pictures taken from site for wall, plaster and door elements and has been able to deliver correct results.

5.4 Contribution to Body of Knowledge

The research has given insight into the use of cutting edge technology in the realm of construction management. It has been observed that there are endless possibilities for implementation of latest trends into construction industry. The cost of technology is within reach of common construction professional as the suggested equipment is not very costly. The decrease in computation cost and increase in computing ability of equipment has also made technology more accessible. It is highly recommended that all construction professionals should be imparted the ability to code in order to inculcate competence necessary to succeed in the cyber age.

5.5 Suggestion for Future Research

The algorithm developed in this research can be further developed and streamlined to be used in bigger projects. The element of automated image acquisition can be added by programming robots to take images at grid locations on set times followed by processing and communication to the concerned stake holders. The element of cost can be added to attain automated cost information from progress information to create cash flows and ascertain

VoWD. The progress information can be uploaded directly to the internet for web based communication of progress information to the concerned personnel. Further integration with IFC model would give interoperability making it possible to extract information and display it on Autodesk Navisworks.

The possibilities are endless and nothing is impossible as long as one has the ability to code.

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