TAMPERE UNIVERSITY OF TECHNOLOGY

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ONLINE MARKERLESS AUGMENTED REALITY FOR REMOTE HANDLING SYSTEM IN BAD VIEWING CONDITIONS

Master of Science Thesis

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ABSTRACT

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This thesis studies the development of Augmented Reality (AR) used in ITER mock-up remote handling environment. An important goal for employing an AR system is three-dimensional mapping of scene that provides the environmental position and orientation information for the operator.

Remote Handling (RH) in harsh environments usually has to tackle the lack of sufficient visual feedback for the human operator due to limited numbers of on-site cameras and poor viewing angles etc. AR enables the user to perceive virtual computer-generated objects in a real scene, the most common goals usually including visibility enhancement and provision of extra information, such as positional data of various objects.

The proposed AR system first, recognizes and locates the object by using the template-based matching algorithm and second step is to augment the virtual model on top of the found object. A tracking algorithm is exploited for locating the object in a sequence of frames. Conceptually, the template is found in each sequence by computing the similarity between the template and the image for all relevant poses (rotation and translation) of template. The objective of this thesis is to investigate if ITER remote handling at DTP2 (Divertor Test Platform 2) can benefit from AR technology. The AR interface specifies the measurement values, orientation and transformation of markerless WHMAN (Water Hydraulic Manipulator) in efficient real-time tracking. The performance of this AR system is tested with different positions and the method in this thesis was validated in a real remote handling environment at DTP2 and proved robust enough for it.

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ABBREVIATION

AR	Augmented Reality
AR-RH	Remote Handling using Augmented Reality
AR-RH-ITER	Remote Handling using Augmented Reality in ITER project
CG	Center of Gravity
CMM	Cassette Multifunctional Mover
CODAC	Command Control and Data Acquisition
DTP2	Divertor Test Platform 2
FOV	Field Of View
IHA	Intelligent Hydraulic and Automation
IHA3D	Intelligent Hydraulic and Automation-3 Dimensional application-(3D-Softwares of IHA)
ITER	International Thermonuclear Experimental Reactor
RH	Remote Handling
RH-ITER	Remote Handling used in ITER project
STD	Standard Deviation
WHMAN	the Water Hydraulic Manipulator
WHjack	the jack attached to Water Hydraulic Manipulator
3D	the Three Dimensional

1. INTRODUCTION

Due to expected levels of radiation inside the ITER vacuum vessel, emitted from activated components and many parts of the machine, ITER Divertor scheduled maintenance requires development of various remotely operable devices and equipments. For RH maintenance operations, a radiation tolerant vision system is required. WHMAN at DTP2 laboratory is a manipulator arm designed and manufactured in IHA. WHMAN is installed on top of the Cassette Multifunctional Mover (CMM), to carry out wide variety of RH operations inside the ITER Divertor, such as cutting, bending and welding of pipes, locking and unlocking of cassettes, etc., during the installation and removal of cassettes [25,21](see appendix B). Here the objective is to investigate the benefits of AR technology in RH-ITER at DTP2 facility. This thesis presents the study ways to help the WHMAN operator to perform his/her RH tasks in more safe and in more efficient manner in poor viewing conditions of ITER. AR techniques have been considered as a user-aiding tool in teleoperation systems. Recent studies show that AR has the potential to improve teleoperation and RH efficiency [1,2,10,11,30]. In other words, AR features should be considered for increasing the operator perception during ongoing task strategies, by improving the operator's vision field on the video feedback. In addition, techniques based on visualizing the 3D graphic knowledge of real scene via AR, are some of the solutions in poor viewing conditions. The AR display method has been recently used in many manipulation systems [27,29,30].

1.1. Motivation

The most common goals of AR technique usually include visibility enhancement and provision of extra information, such as positional data of various objects. Because of the neutron activation in ITER Divertor (see appendix B), which forbids direct human access inside the reactor, teleoperation, inspection and maintaining should be done remotely. Utilizing of the AR techniques can be considered as an additional ingredient to the total RH and teleoperation renewal [1]. In this research, it is intended that the resulting of the AR system allows the user’s view in the RH-ITER mock-up to be enhanced and augmented with additional information generated by a computer. The system should also integrate with the task management and planning systems [3]. In addition, it is intended, that the AR system should be able to assist the operator as a visualization tool in the RH-ITER.

1.2. Objective

The objective of this thesis was to develop a markerless AR in bad viewing conditions as a user interface for the ITER project. This specially includes the following goals:

- The tracking the algorithm exploited for locating the object in a continuous sequence of frames in the RH-ITER
- Producing a virtual environment, so that the computer-generated of 3D Cad-models are superimposed on a user’s view in the real scene
- Specifying the orientation and transformation of WHjack (Jack Tool of WHMAN) in near real-time
- Increasing the accuracy for measurements according to the WHjack lengths and distance by using a suitable Cad-model
- Enhancing visibility and provision of extra information, such as positional data of various objects
- Investigating how the RH at the DTP2 can benefit from the AR technology.

1.3. Scope of the Thesis

This thesis describes the use of a markerless AR interface in RH to address the following issues:

- Recognition and localization of a markerless object by using the template matching algorithm, then augmenting the virtual model on a top of the found item
- Determining and displaying the location and the orientation of the object in three-dimensional workspace using two-dimensional workspace
- Providing the immediate feedback to assist the operator for control the system in near real-time

1.4. Outline of the Thesis

The thesis begins with an overview of RH and RH-ITER and a summary aspect of a markerless AR-RH in chapter 2. Chapter 3 gives a summary explanation about the template based matching algorithm and camera calibration theoretical topics. Implementations section of thesis including AR program design is discussed in chapter 4. Results, evaluations, and optimization topics are explained in chapter 5. Ongoing and future work is investigated in chapter 6 and the conclusions are drawn in the chapter 7.

2. REMOTE HANDLING

This chapter is an overview of some important terms in RH and RH-AR definitions and applications.

2.1. Definition

Humans have been practicing RH for many centuries. The Blacksmith subsequently developed special tools, called tongs, to manipulate and heat the workplace in hot embers and during forging. However, the key developments in RH and manipulation took place in the middle of the last century during the pioneering days of the nuclear industry, when the extreme radiation hazards to humans became apparent. Nowadays there are extremely sophisticated computers include controlled tele-robotic systems and virtual environments that allows users to plan and execute complex tasks that would otherwise impossible to undertake because of the nature of environment, or the extreme distance involved [13]. Due to expected level of radiation in ITER environment, the need for RH is clear. The RH system used for maintenance at the ITER environment includes robotic devices, virtual reality and wide range of specialist tools. Inspections have provided opportunities in RH research area, design and utilization of alternative approaches.

RH is the knowledge which combining the technologies of teleoperation or telerobotics with the management and organizational knowledge required for preparing and running a remote operation application. RH is to enable an operator to do manual handling work at operation site without being physically present at that scene.

2.2. ITER Remote Handling

When the real activated ITER operation begins, it will be impossible to make changes, conduct inspections or repair any of operations in the activated areas other than by RH. Therefore, robust RH techniques will be necessary to manipulate and exchange components in ITER project [5]. RH has been well developed for a fusion device. The physical side of ITER operations requires the development of various remotely operable device including robotic manipulators, tooling, inspection equipments and transports. The technological expertise requires to design and operate. These types of systems covers mechanical, electrical and electronic engineering, software, real time control, usability pneumatics and hydraulics, welding and cutting. Briefly, RH system ensures that ITER components can be maintained to meet availability goals and leading to effective reactor operations [7].

2.3. Remote Handling Challenges

There are several challenges using RH-ITER. The most important among them are follows:

- Sensing the environment; due to effect of high radiation to sensors, there is a challenge to provide environment-sensing equivalent to being in the environment
- Equipment reliability; the access to equipment is severely restricted and a failure in operation has serious term
- Command and control; require to high-level commands of equipment and require equipments to successfully performs commands very reliable, in other hand the operator’s focus should be on task and many types of equipment, must be coordinated to perform task [16]

The viewing needs for RH activities are correlated to the level of task automation. A simple task with a high level of automation will only require a low level of visual control and a final check of the situation is probably sufficient. For highly skilled operations, a real-time high quality viewing system is essential to guarantee the success of the RH operation [6].

2.4. Instrumentation and Control

A successful RH process is defined with its ability to specify and integrate together the appropriate technologies, organizational and management activities.

Monitoring and controlling RH environment provided by an integrated supervisory control and a data acquisition system, which also includes a virtual model of the scene and its equipment control systems.

Briefly, some characteristics of the instrumentation and RH-ITER control system are as follows:

- Provides control and monitoring of the mechanical and electrical system
- Capable of both real time on-line monitoring of the RH equipment and off-line simulation for procedure planning and evaluation
- Instrumentation and control in ITER will have a central control room for the overall site command control and data acquisition (CODAC) system [8]

It is clear that on-line monitoring of the remote environment and robot modeling in ITER environment has accuracy limitations, therefore this system cannot be used as primary reasonable viewing system.

2.5. Remote Handling and Augmented Reality

Augmented reality (AR) systems merge a computer-generated graphics with a view of the real physical world. Ideally, the graphics should be perfectly aligned with the real physical world. Perfect registration requires the information to have the accurate knowledge of the physical world and the spatial relationships between the world, the display and the viewer. However, in many real-world situations, the available information is not accurate enough to support perfect registration [2].
AR has often been defined in various ways. Either a more conceptual point of view has been taken or emphasis has been placed on technological point of view, which often refers to the display or tracking device was used. In this thesis, we focus on AR system with having the following properties [24]:

- Combine real and virtual objects in real environment
- Run in real time or near real time
- Register real and virtual object in respect to each other.

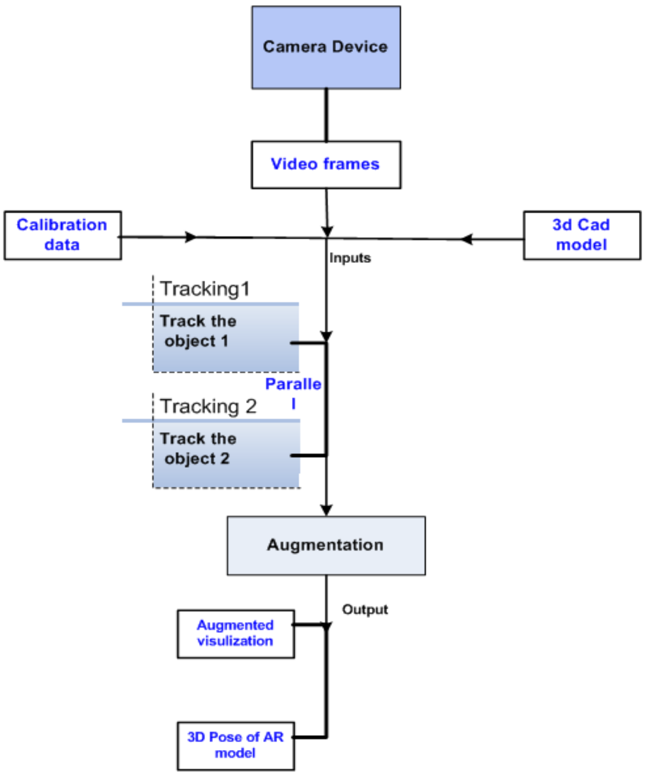

Figure 2-1. *Framework algorithm of a markerless AR-process*

AR system is an approach to create the superposition of additional scene data into the video stream of a real camera. The technical and algorithmic demands for online AR are very challenging, here we follow the frame work algorithm is explained in Figure 2.1.
The tracking part and registration are two difficult parts in trying to give reasonable augmentation process. Computation of camera pose must be very fast and reliable, even in uncooperative environments with difficult illumination situations. This requires high computational demands on the system. The first step is to get video frames

continuously. We pay particular attention to developing AR technology for RH applications.
The process includes, online video streams, calibrating and augmenting images as they come in. There is no marker in the scene. As we need to achieve robust real-time performance, the simplified or engineered scene and object structure are needed.

In RH technology, a telemanipulator is a device that is controlled remotely by a human operator. At increasing levels of sophistication, the device may operate somewhat independently in matters such as obstacle avoidance. Two major components of manipulator are the visual and control parts. Study of control part is beyond the scope of this thesis. A camera (see Figure 2.2) provides a visual representation of the view from the manipulator in real the RH environment.

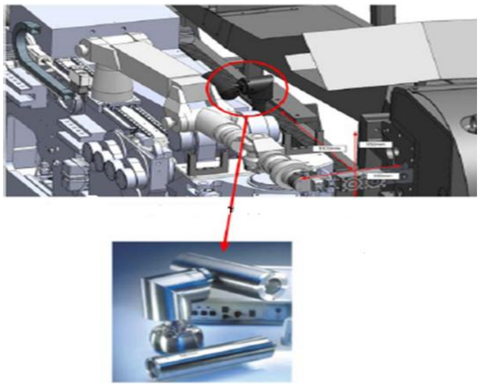

Figure 2-2. *Camera position in RH-ITER project [26].*

2.5.1. Related Work

From a historical point of view, the AR has long been used in robotic environment using operator's position and orientation awareness by providing a global view in robotics, teleoperation and recently in RH. This chapter presents some recent applications of AR used in teleoperation and RH.
Hirokazu Kato et al presented a pose-tracking (ARToolkit) library with six degrees of freedom, using square fiducial and a template-based matching approach for recognition. [23]. ARToolKit is available as open source under the GPL license and is still very popular in the AR community [23].
Sugimoto et al. use AR to assist remotely a user in robot teleoperation by using a virtual robot onto the center of the real environment image, captured by a camera mounted on a robot. This helps a operator to understand the spatial relationship between the robot and the environment [28]. Collett et al. applied AR for debugging robot applications. They superimposed virtual information to develop robot's operator understanding of the robot's scene view [29]. Wagner et al. by using a fixed overhead camera and ARToolkitPlus software could track the markers attached to the ground robots in the test environment [9].

The most of the these AR applications in robotics rely on markers for recovering the camera position and orientation.

Chen et al. tracked the pose of a camera mounted on a robotic helicopter using natural features. The position of the virtual marker on the image plane can be continuously updated by tracking natural features in the environment [10]. Another important application of AR is in the International Space Station (ISS). Using AR benefits the operator's situational awareness in this robotic environment in some critical applications such as transferring the materials from the space shuttle and the deployment, capture and maintenance of satellites. Operators must frequently rely on cameras mounted on the manipulator. Artificial or AR cues can be useful assisting devices enhancing the operator’s situational awareness [12]. Unlike the conventional robotics, the RH always involves a human being within the process. The main handling device is a manipulator, not a robot, because the majority of RH tasks need to human vision and intelligence [7].

AR is a technology enabling a user to provide virtual objects (3d Cad- models) in a real environment by capturing and analyzing the camera images continually.

2.6. 3D Cad-Modeling

3D modeling for industrial design, movies and games requires a user interface to design 3D structure consisting of thousands of elements. AutoCAD R12 is the desired software for creating the 3D Cad-model of our desired object. Here the 3D-model of our desired object was created using AutoCAD R12.

This chapter summarizes human visual perceptions, which are relevant for the design of WHjack 3D Cad-model. 3D cad-modeling steps include the following steps:

- Creation the dwg format of WHjack. It is better to consider the unique features for creation the Cad-model
- A 3ds format rebuild as a triangulated surfaces form. Surfaces of the 3D Cad-model define the details of the shape model. The balance between surfaces and details increases the real-time property of tracking process (see Figure 2.3)

In implementation step of AR process, a Cad-model has to be able to match with the real manipulator image in online video, this makes it easier to find and track the manipulator.

The triangulated surfaces of the model define the details of a desired object. On the other hand, a precise model with high numbers of surfaces causes the latency in tracking time of the AR process.

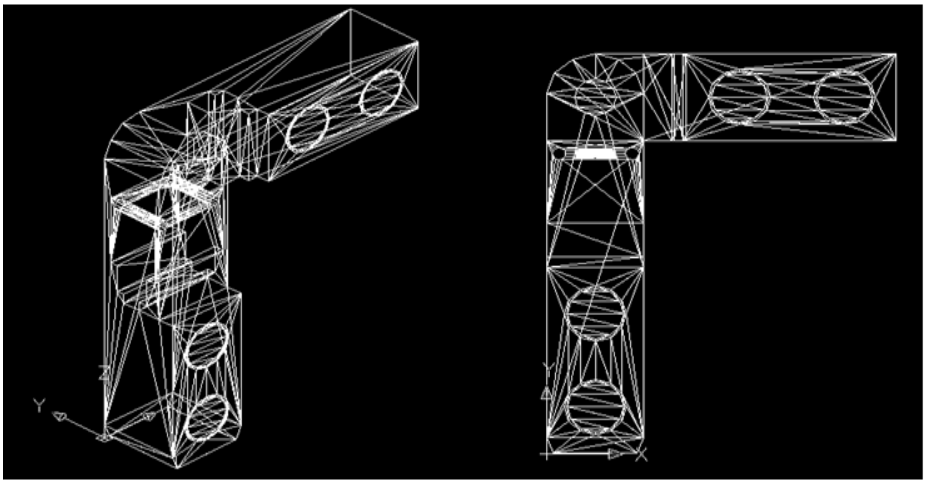

Figure 2-3. *Triangulated surface of WHjack Cad- model*

2.6.1. Triangulation and Mesh Simplification

Triangulation process in AutoCAD performs triangulation of a set of 3D points with compulsory interconnections between the points. The outcome is represented by 3Dfaces entities. The outcome is made up of Polyline entities optionally interpolated.

Mesh simplification (see Figure 2.4) is the process of reducing the number of faces used in the surface while keeping the overall shape, volume and boundaries preserved as much as possible. It is the opposite of subdivision. In this thesis, the simplification process was done manually. In addition there are different algorithms to reduce the number of surfaces. This suitable simplification decreases the time of tracking [14].

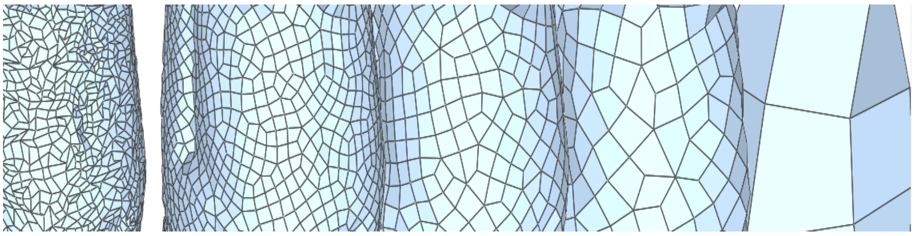

Figure 2-4. *Surface triangulate mesh simplification (left to right) [14]*

The reconstruction of Cad-model requires the knowledge of interior camera parameters that will be explained in the next chapter. Interior camera parameters determine the cameras characteristics, lateral image shift and optical distortions.

2.6.2. Gravity Center of the Cad-Model

The gravity center (CG) is a geometric property of any object. The CG is the average location of the weight of an object. We can completely describe the motion of any object through space in terms of CG translation, from one place to another and the rotation of the object around its CG (if it is free to rotate). If the object is confined to rotate about some other point, like a hinge, we can describe its motion.

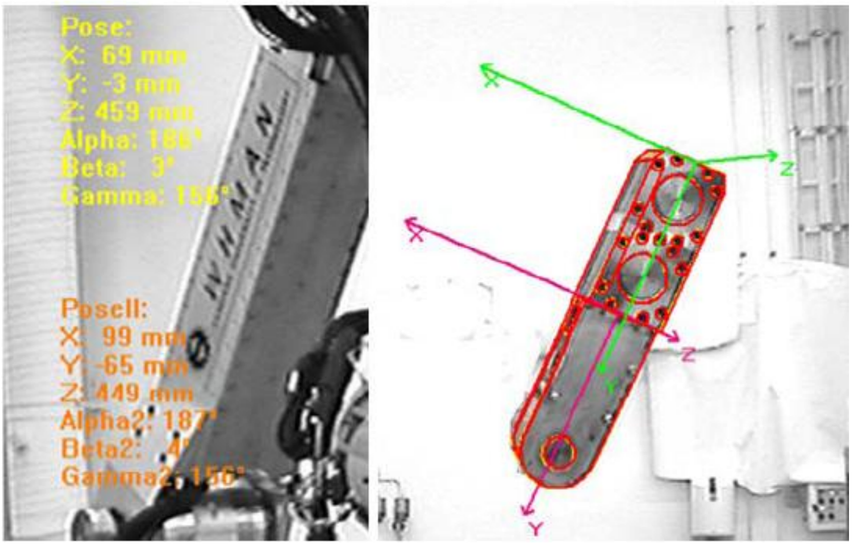

Figure 2-5. *Two gravity centers of WHjack models were tracked in AR process*

In general, determining the CG is a complicated procedure because the mass (and weight) may not be uniformly distributed throughout the object. If the mass is uniformly distributed, the problem is greatly simplified. If the object has a line (or plane) of symmetry, the CG lies on the line of symmetry. For a solid block of uniform material, the center of gravity is simply at the average location of the physical dimensions [15].

Here, the definition of desirable centre of gravity coordinates of a Cad-model depends on the desired object definition. The gravity center position of Cad-model augmented in real object of video stream will be found during the AR process, continuously. Figure 2.5 shows, how two gravity centers are used for length measurement during the AR process. One of the AR process goals is determination of object pose. Therefore, the CG as a desirable position is needed. In this project, the CG position is converted using Google Sketch up software.

3. TEMPLATE MATCHING ALGORITHM

One of the most popular methods to extract useful information from image sequences is the template based matching approach. The tracking of a certain feature or target over time is based on the comparison of the content of each image with a sample template.

Writing robust recognition algorithm for a particular type of the object can be quite cumbersome. Furthermore, if the object to be recognized changes frequently, a new algorithm must be developed for each type of object. Therefore, a method to find any kind of object that can be configured simply by showing the system a prototype of the class of the objects to be found, would be extremely useful.

Halcon functions can help to fulfils shape-based matching algorithm to find objects based on a Cad-model template and to locate them with sub-pixel accuracy. The template matching approach can be found useful for several purposes. It can be used to detect the presence or absence of the object and it can be used to distinguish between different types of objects.

The simplest kind of template matching algorithm is based on the raw gray values in the template and the image. The definition of template matching is about finding the similarity between the template and image [19].

To find a rotated object, we should create the template in multiple orientations. In other word, we discretize the search space of rotations in a manner that is analogue to the decretization of translations that is imposed by the pixel grid. Here, the goal is track the object (WHjack template Cad model), if even slightly changes the 3D orientation of the camera in respect to the object [19].

The tracking performance depends on detected and tracked features. A feature can be detected and tracked and it can be detected but not tracked, or it cannot be tracked. This tracking is difficult because of the articulated structure, which creates many degrees of freedom. Therefore, having the accurate Cad-model from different sides can simplify the tracking process. In this experiment, edge of the object should be distinguishable from the background but in industrial environments, detection of object edges is quite difficult, therefore creating precisely unique features in 3D Cad-model in respect to the real object compensating the lack of busy environment for finding the edge of object.
Figure 3.1 shows three positions of desired object with different level of tracking using a template-matching algorithm. Left and middle images show accurate tracking results and the 3D Cad-models coincide to real objects in video continuously. Right image shows the AR with bad tracking and bad augmentation.

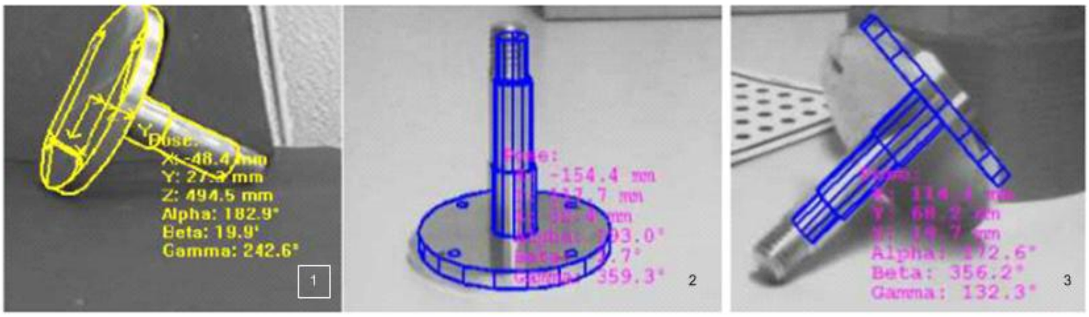

Figure 3-1. *Projection of CAD model, (1, 2), accurate 3D-tracking, 3) Wrong 3D-tracking.*

3.1. Camera Calibration

The calibration procedure is a basic step to find relationship between the real world and image coordinates. The pinhole camera establishes the mathematical relationship between central projections of 3D object plane to 2D image plane. Camera calibration is about finding the quantities internal to the camera affecting the imaging process. These internal quantities (see Figure 3.2) include:

- position of image center in the image
- focal length
- different scaling factors for row pixels and column pixels
- skew factor
- lens distortion

Interested reader can find the description of above parameters in [18].

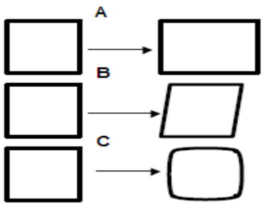

Figure 3-2. *A) Different scaling, B) Skew factor, C) Lens distortion*

Good calibration is important when we need to reconstruct a world model and interact with the world. The internal camera parameters (intrinsic parameters) define a pixel coordinates of image point in respect to coordinates in camera reference frame. If world and image points are represented by homogeneous vectors, central projection is a linear transformation (see Figure 3.3).

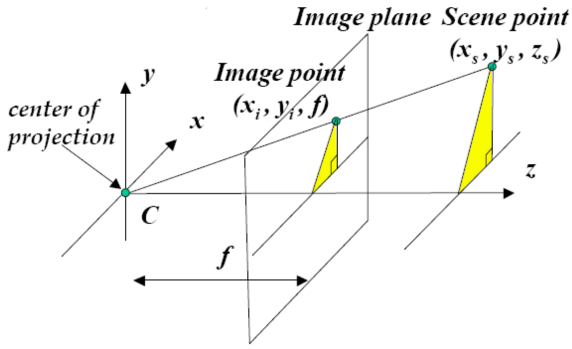

Figure 3-3. *Liner transformation of camera central-projection*

In general, camera calibration means the exact determination of the parameters that model the projection of any 3D world point P^w into a sub-pixel in the image. This is important, if the original 3D pose of an object has to be computed using an image, for example measuring of industrial parts. The transformation from world coordinates to camera coordinates is:

$$\begin{bmatrix} P^c \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} R & t \\ 000 & 1 \end{bmatrix} \times \begin{pmatrix} P^w \\ 1 \end{pmatrix} \quad \text{(Eq 3.1)}$$

The combination of an area scan camera with a non-ideal lens, effects a perspective projection and that may show radial distortions [17].

3.2. Calibration Plates

The simplest method to determine the interior camera parameters, is the use of standard calibration plates of Halcon [17]. The camera calibration procedures require a plate with known dimensions.

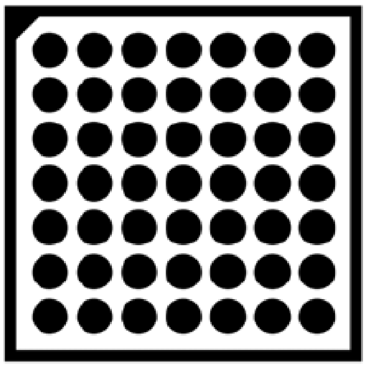

Figure 3-4. *Created calibration plate*

The coordinate system of the calibration plate is located in the center of all marks; its z-axis points into the calibration plate, its x-axis to the right, and its y-axis downwards (see Figure 3.4).

3.3. Camera Parameters

Interior camera parameters describe the characteristics of the used camera, especially the dimension of the sensor itself and the projection properties of the used combination of lens, camera, and frame-grabber. The camera model contains the following eight parameters [17]:

- Focus: Focal length of the lens
- Kappa: Distortion coefficient to model the pillow or barrel shaped distortions caused by the lens
- Sx: Scale factor along x-dimension. For pinhole cameras, it corresponds to the horizontal distance between two neighboring cells on the sensor
- Sy: Scale factor along y-dimension. For pinhole cameras, it corresponds to the vertical distance between two neighboring cells on the sensor
- Cx: Column coordinates of the image center point (center of the radial distortion)
- Cy: Row coordinate of the image center point (center of the radial distortion)
- Image Width: Width of the sampled image
- Image Height: Height of the sampled image

3.4. Robust Template Matching

Another goal of template matching algorithm is finding of the object in images even if it is occluded or disturbed or some part of the object is missing. Furthermore, the object should be found even, if there is a large numbers of disturbances on the object. Moreover, the object should be found if there are sever nonlinear illumination changes.
This template-matching algorithm is robust to nonlinear illumination changes. Actually, edges are not (or at least very little) affected by these changes and therefore frequently are used in robust matching algorithms [18].

3.5. Illumination

The goal of illumination in machine vision is to make the important feature of an object visible and suppress undesired features of the object. It should be considered how the light interacts with the object. One important aspect is the spectral composition of the light and object. We can use monochromatic light on color object, to enhance the contrast of desired object features. The other important feature is the direction of illumination. It can be used to enhance the visibility of a feature.

Illuminators for machine vision have historically been designed by adapting readily available, mass-produced illumination technologies to suit individual machine vision applications. In its simplest form, 2D inspection involves detecting for the presence or absence of a product, property and feature. Vision applications commonly include character or feature recognition while more advanced systems can perform physical measurements on parts and do not require complex illumination schemes. A single light source that provides a soft and repeatable illumination is usually adequate. The most important consideration for these applications besides "does it work?" should be "is it reliable?"

Reflection of light is either specular (mirror-like) or diffuse depending on the nature of the interface (see Figure 3.5) [4].

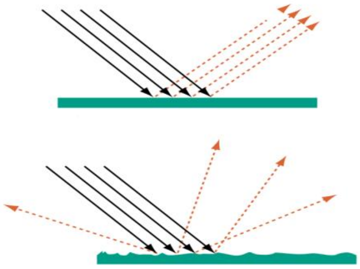

Figure 3-5. *Specular reflection, smooth surface and diffuse reflection, rough surface* [4].

Reflection at the metal and dielectric surfaces, for example glass or plastics, causes light to become partially polarized. Polarization occurs for diffuses as well a secular reflection.

Most real surfaces exhibit specular as well as diffuse reflection. The illumination and viewing directions at different points on a surface are different in respect to a fixed light source and a fixed viewpoint [18].

3.5.1. The ITER Remote Handling Illumination

The behavior of light reflection during the AR depends on the illumination conditions. Really, the useful information about real illumination conditions of RH-ITER has not been produced sufficiently. It is clear the radiation will effect on camera characteristics, image quality and color. In this environment, the AR system can artificially reintroduce color and shading cues of the environment as a displayer for the RH operator [3].

3.5.2. Illumination and Shape-Based Matching Algorithm

In many vision applications, it is useful to be able to separate out the regions of the image, corresponding to objects in which we are interested, from the regions of the image that correspond to background. Threshold process often provides an easy and convenient way to perform the segmentation on the basis of the different intensities or colors in the foreground and background regions of an image.

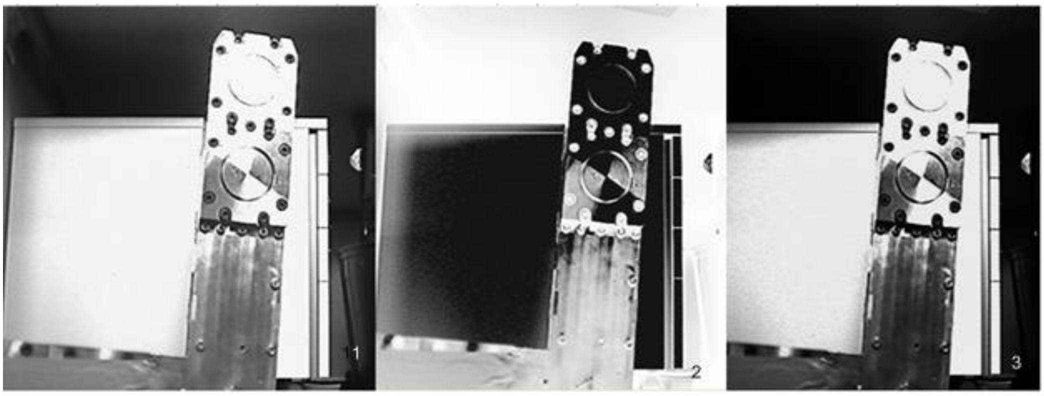

Figure 3-6. *(1) Black and white image of WHjack and (2, 3) Different gray scale between (0-255)*

The threshold operation input can be a grey scale or color image. In the simplest implementation, the output is a binary image representing the segmentation. Black pixels correspond to background and white pixels correspond to foreground or vice versa. In simple implementations, the segmentation is determined by a single parameter known as the intensity threshold and each pixel in the image is compared with this. If the pixel intensity is higher than the threshold, the pixel is set to white in the output. If it is less than the threshold, it is set to black (see Figure 3.6).

If the threshold is chosen incorrectly, the extracted object typically becomes larger or smaller because of the smooth transition from the foreground to the background gray value. This problem is especially grate if the illumination can change, since in this case the adaption of the threshold to the changed illumination must be very accurate. Therefore, a segmentation algorithm that is robust in respect to illumination changes is extremely desirable.

Using the features being robust to nonlinear changes due to applying the AR process is one of the AR goals. The edge features are not (or at least very little) affected by illumination changes and therefore, the edge feature are frequently used in the robust matching algorithms. In most case the accuracy of measurement can derived from the segmentation result critically depend on choosing the correct threshold for segmentation.

The boundary of the segmented region or sub pixel-precise contour moves if the illumination changes or threshold are chosen inappropriately. Therefore, the goal of robust segmentation algorithm must be to find the boundary of the object as robustly and accurately as possible [18,19].

4. AR PROGRAM DESIGN

There are five basic steps in the programming of the mrkerless AR interface:

1. Calibrating the camera
2. Creating a 3D Cad-model of WHjack
3. Training
4. Visualization
5. Optimization

4.1. Required Software and Hardware

The Software used in this project includes:

- MVTec HALCON is the comprehensive proprietary software with an integrated development environment (IDE) for machine vision
- DirectShow was used as a driver between frame-grabber and Halcon software[17]
- AutoCAD Release 12 and Google Sketch up for creating and modifying the virtual model

The hardware used in this project includes:

- PC Core2, 3.37 GB of RAM
- ZB5451IR/AF Camera (see appendix C). The Camera (CCD) specifications such as zoom ability, high resolution and focal length were chosen depend on RH scene and objective of process
- Analog frame-grabber that is supported by Halcon software
- Calibration plate

4.1.1. Scheme of the System

Figure 4.1 shows the scheme of the AR-RH system. It is composed by two main parts: the RH site and the local site, includes the capture and the subsystem. The RH site is composed by WHMAN and its environment. The operation of the WHMAN will be done according the planned tasks and interaction capabilities based on augmented reality together to other software IHA3D. IHA3D is being developed by IHA and it consists of virtual environment graphical software.

The capture subsystem is composed by camera (ZB5451IR/AF) connected to frame-grabber (capture card), support within a PC system. The objectives of these elements are to capture the movements in RH site and send it to reception subsystem for augmented visualization.

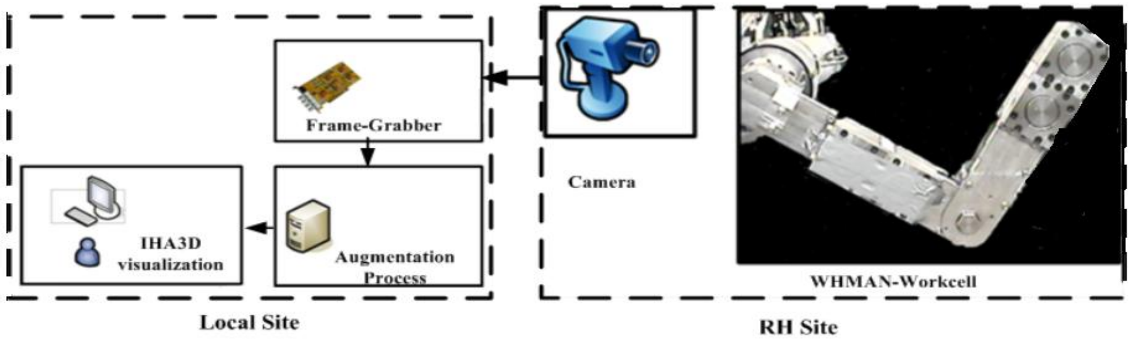

Figure 4-1. *Scheme of the system*

The video from the RH site received in process subsystem will be augmented to be showed to the operator.

4.2. Camera Calibration

The simple method to generate the plate for calibration is using the Halcon operators. The first step is, to take a set at least 10 to 20 images of suitable images. The images should be taken with special conditions, for example the calibration plate has to be completely visible and reflections on calibration plate should be avoided. The size of plate should be at least ¼ of image display. The set of the images should appear in different positions and orientations (see Figure 4.2).

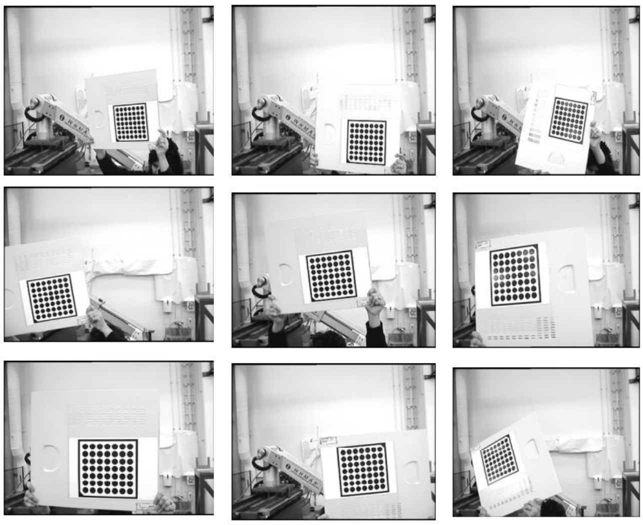

Figure 4-2. *Camera Calibration plate in real RH scene.*

Figure 4.3 shows the basic steps of calibration process. The first step is setting the initial camera parameters that were defined based on camera specifications and captured images [17]. The following initial values were used:

Focus: 0.0038
Kappa: 0.0
Sx: 5.5e-006
Sy: 5.5e-006
Cx: 404.991
Cy: 212.697
Image Width: 720
Image Height: 560

All camera parameters were determined by a simultaneous minimization process. For this, the known 3D model points (with coordinates X, Y, Z) are projected in the image and the sum of the squared distance between these projections and the corresponding image points is minimized. If occurs the minimization converges, the exact interior camera parameters are determined by this algorithm.

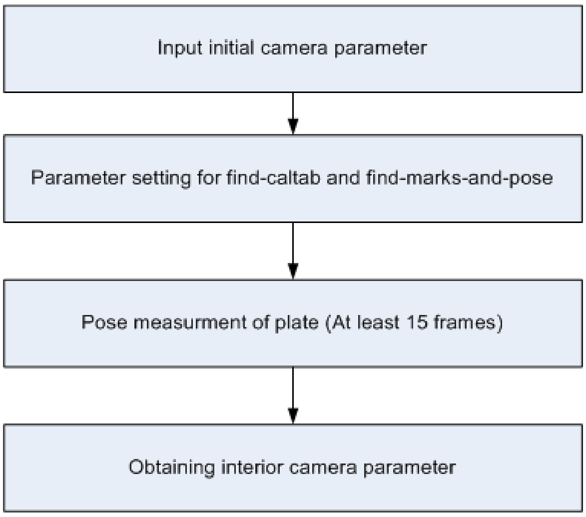

Figure 4-3. *The basic steps of calibration process using Halcon*

Since this algorithm simultaneously handles correspondences between the image and the model points of different images, it is also called multi-image calibration. The Figure 4.3 shows the basic steps of calibration process.

4.2.1. Results

The obtained interior camera parameters using two plates with different size are illustrated in table 4.1. The obtained interior camera parameters are inputs of main augmentation process.

Table 4-1. *The interior camer aparameters using two plate*

Parameter	Calibration with big plate	Calibration with small plate	Description
f	0.00449715	0.00457949	"Focal length of the lens [meter]"
κ	-7836.79	-9613.03	"Radial distortion coefficient [1/(meter*meter)]"
Sx	5.88852e-006	5.87568e-006	"Width of a cell on the CCD-chip [meter]"
Sy	5.5e-006	5.5e-006	"Height of a cell on the CCD-chip [meter]"
Cx	376.392	378.149	"X-coordinate of the image center [pixel]"
Cy	292.952	302.079	"Y-coordinate of the image center [pixel]"
ImageWidth	720	720	"Width of the video images [pixel]"
ImageHeight	576	576	"Height of the video images [pixel]"

4.3. Creating a 3D Cad-Model of WHjack

One possible way to create a suitable dxf file is to create a 3D model of the object with the Cad program of AutoCAD. All surfaces (not only edges) of the object should be modeled.

For example, the lines that define the object edges will not be used by Halcon, because they do not define the surface of the object. Once the model is completed, it should be stored in dwg format. The next step is triangulation of Cad-model. A suitable way is using of triangulation command of AutoCAD. The final triangulated dxf file is ready to use in training program as an input dxf Cad-model.

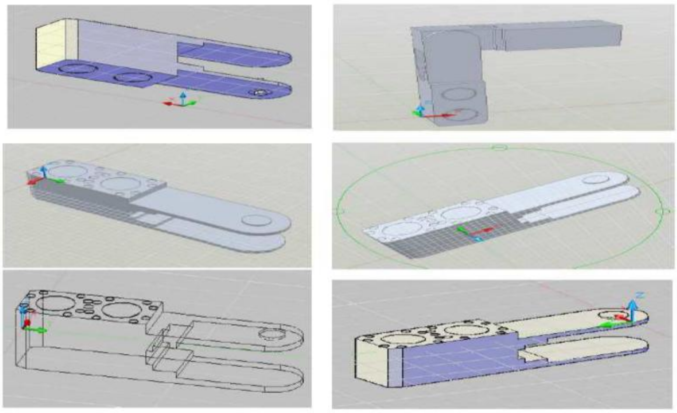

Figure 4-4. *3D-Cad models WHjack*

It is often possible to save the 3D model in the proprietary format of the Cad program and to convert it into a suitable dxf file by using a Cad file format converter that is able to perform the triangulation (see Figure 4.4).

4.3.1. 3D Object Model of WHjack

Next step is to read a 3D object model from a dxf file. The operator can read the contents of the dxf file and convert them to a 3D object model.
One of the output parameter in this step (dxf status), contains information about the number of 3D faces were read. This 3D-object model operator supports the following dxf entities, Polyline, Polyface meshes, 3Dface, Line, Circle, Arc, Ellipse, Solid and Block insert. Two-dimensional linear elements that consist of just two points are not used because they do not define a face. Thus, elements of the type Line are only used if they are extruded. The curved surfaces of extruded dxf entities of the type Circle, Arc, and Ellipse is approximated by planar faces.
The accuracy of this approximation can be controlled with the two generic parameters: minimum number of points and maximum approximate points. The minimum number of points defines the number of sampling points that are used for approximation of the dxf element Circle, Arc or Ellipse and always refers to the full Circle or Ellipse. The maximum approximate error defines the maximum deviation of the xld contour from the ideal Circle or Ellipse, respectively. The determination of this deviation is carried out in the units used in the dxf file. For the determination of the approximate accuracy, both criteria are evaluated. Then, the criterion that leads to the more accurate approximation is used [17].

4.4. Training Process for Cad-model of WHjack

During the matching process, the shape representations would be used to find out the best-matching view, from which the pose is subsequently refined and returned. In order to create the model views correctly, the camera parameters that will be used for the matching must be passed as input.

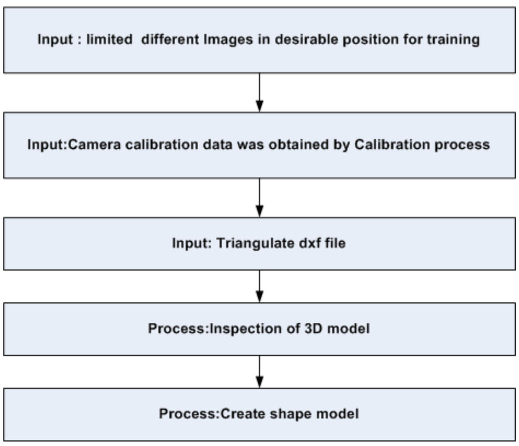

Figure 4-5.*The basic steps of training process based template-matching algorithm.*

The camera parameters are necessary to determine the scale of the projections by using the actual focal length of the camera. Furthermore, they are used to treat radial

distortions of the lens correctly. Consequently, it is essential to calibrate the camera before creating the 3D shape model [17].
As a case study, this program uses shape-based matching algorithm to find the 3D pose of WHjack that exhibits a six degrees of freedom motion. The prepared object model and camera parameters are used as an input in the training process using Halcon. The basic steps is shown in Figure 4.5. The first three steps of algorithm were explained in previous sections.

4.4.1. Inspection Process

In inspection step, the 3D shape model is generated by computing different views of the 3D object model within a user-specified pose range and the Cad-model dimension scale is fitted to real object with the user input, manually.
In this case, inspection process will be used to determine the desired pose range in which the 3D shape model is to be created. Inspection process (see Figure 4.6) can also be used to find the right values for the input control parameters of create a shape model operator.
In this step, several windows are opened to interact with the user (see Figure4.7). In this case, the background images must be passed in the input images as a tuple (multi valves). If no background images are available, an empty tuple must be passed instead. The number of the currently displayed background image is displayed in the upper left image corner.

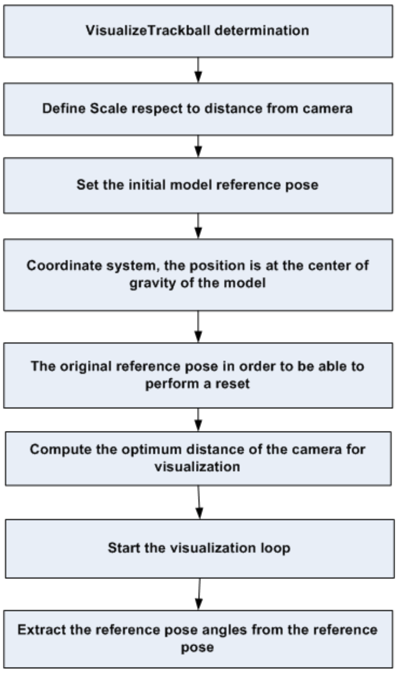

Figure 4-6.*Inspection process steps*

If the current mouse mode is set to 'Move Camera' the mouse can be used to change the current camera view (see Figure 4.8). The position of the camera on a virtual sphere around the 3D object model can be changed by moving the mouse while holding the left mouse pressed. For this, a virtual trackball indicates around which axis the camera should be rotated. If the mouse is inside the circle, the camera is rotated around the x and y-axis while otherwise the rotation is performed around the z-axis.

Set Reference Pose	Increase MinFaceAngle	Reset Reference Pose
Add to Pose Range	Decrease MinFaceAngle	Reset Pose Range
Next Image	Mouse Mode: Move Camera	Hidden Line Removal
Previous Image	Mouse Mode: Move Image	Exit

Figure 4-7. *Several input buttons in the 3D inspection step for creating the desired shape model.*

The distance between the 3D object-model and the camera can be changed by moving the mouse in vertical direction while holding the right button pressed. If the current mouse mode is set to 'Move Image', the background image can be moved by using the left mouse button. Other window visualizes the position of the camera (yellow coordinate system) on the virtual (blue) sphere around the 3D object model (see Figure 7.8). Additionally, the 3D object model is shown from the current camera reference. The camera reference pose determines the mean pose under which the 3D object model is seen in the images, in which the 3D object model should be found.
The range of poses under which the 3D object model should be found is specified by using spherical coordinate longitude and latitude. If latitude and longitude both are zero, the current viewing direction coincides with the viewing direction of the reference pose. After moving the camera on the sphere, the yellow camera coordinate system is updated accordingly.

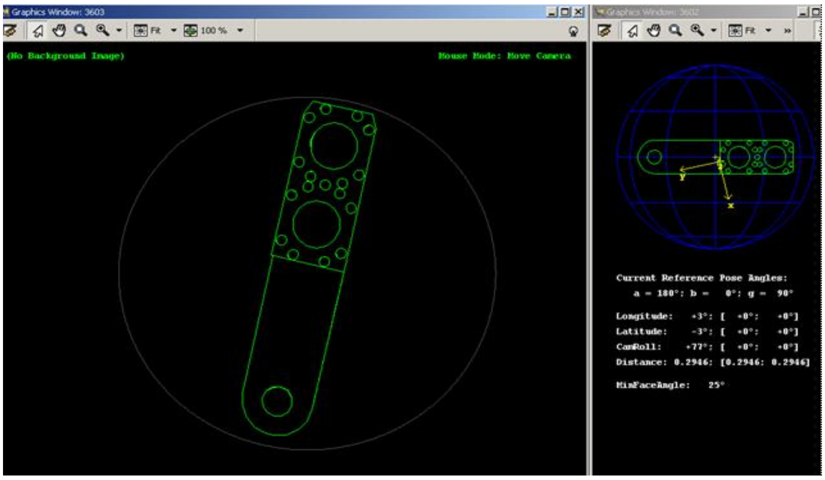

Figure 4-8. *Fitting the scale and dimension in train process by user, manually [17]*

The camera rotation angle around the z-axis of the camera in respect to the reference pose and the distance between the centre of the 3D object-model and the camera, as well as the minimum face angle are displayed. In addition, the values of the camera pose (longitude, latitude, camera roll angle, and distance) and respective intervals of the selected pose range are displayed [17].

4.4.2. Creation the Shape Model of WHjack

The shape model creation, procedure (see Figure 4.9) prepares a 3D object model, as a 3D shape model used for shape-based matching algorithm. The 3D object-model must previously be read from a dxf file. In this step, the 3D shape model is generated by computing different views of the 3D object-model within a user-specified pose range.

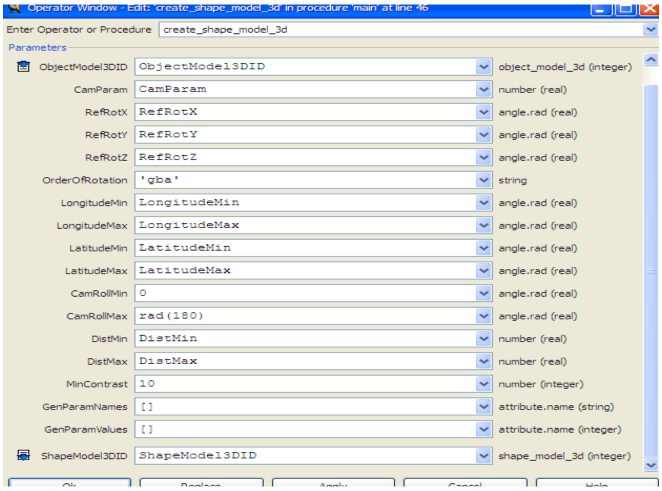

Figure 4-9. *Inputs and outputs of creation shape model process,*

The views are automatically generated by placing virtual cameras around the 3D object model and projecting the 3D object model into the image plane of each virtual camera position. The shape representations of all views are stored in 3D shape model. The 3D shape model representations are used to find out the best-matching view, from which the pose is subsequently refined and returned. The camera parameters are necessary, to determine the scale of the projections by using the actual focal length of the camera and to treat radial distortions of the lens correctly [17].

4.5. Visualization

The shape model created in previous step (training process) is an input for visualization process.

4.5.1. Find 3D Shape Model of WHjack

In this step, the 3D shape model created previously will be found using a template matching algorithm. The 3D pose of the found instance of the model is returned in Pose output (see Figure 4.10). It describes the gravity center pose of the augmented 3D object model in the camera coordinate system.

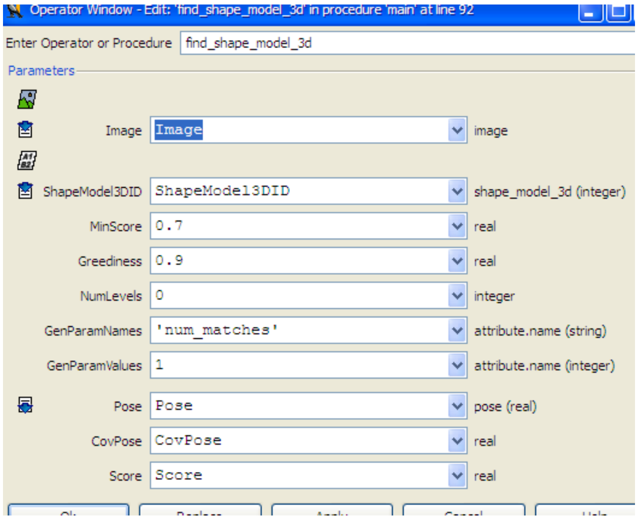

Figure 4-10. *Find-shape-model-3d parameters [17]*

The Pose resulting refers to the original 3D object model coordinate system used in the dxf file. Finally, the score of each found instance is returned in score parameter. The score is a number between zero and one, which is an approximate measure of how much of the model, is visible in the image.

4.5.2. Projection and Augmentation

This step determines the edges of a 3D object model into the image coordinate system and augments the 3D object to the image by projecting the shape model and the pose of the match.

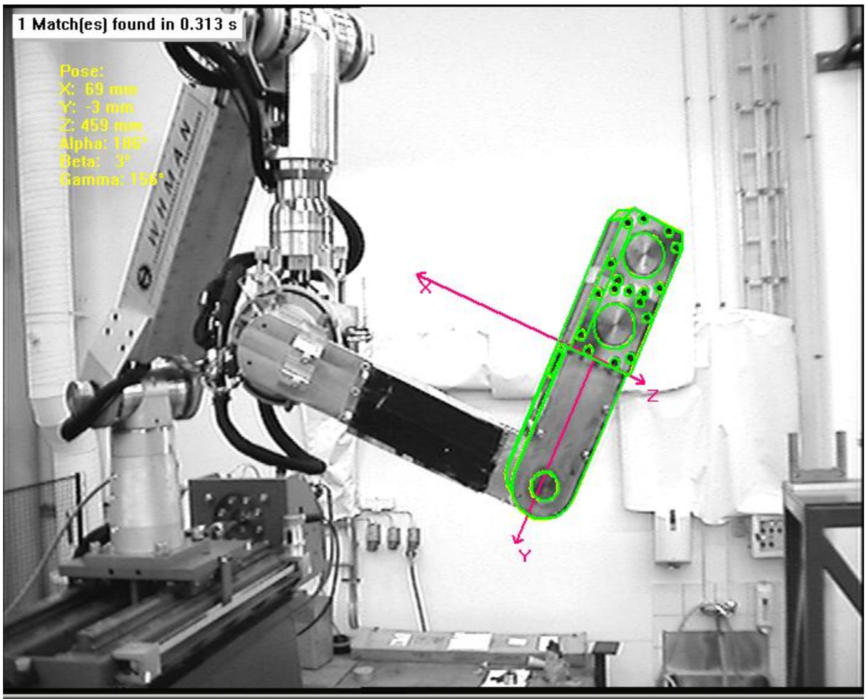

Figure 4-11. *The final augmentation*

The coordinates of the 3D object model are given in the 3D world coordinate system. First, they are transformed into the camera coordinate system using the given pose then these coordinates are projected into the image coordinate system based on the interior camera parameters. The interior camera parameters describe the projection characteristics of the camera and the pose describes the position and orientation of the world coordinate system in respect to the camera coordinate system [17].

Additionally, coordinate procedure projects the world origin to the image and then project the coordinate axis to the image in respect to the gravity center of Cad-model. The pose procedure projects the reference point and displays the pose at the projected reference point (see Figure 4.11).

5. RESULTS

The markeless AR user interface enables us to augment 3D shape model and visualize the found matches in the image also it enables us to project the coordinate system of the 3D object model and display the parameters of the found pose in a video stream (see Figure 5.1).

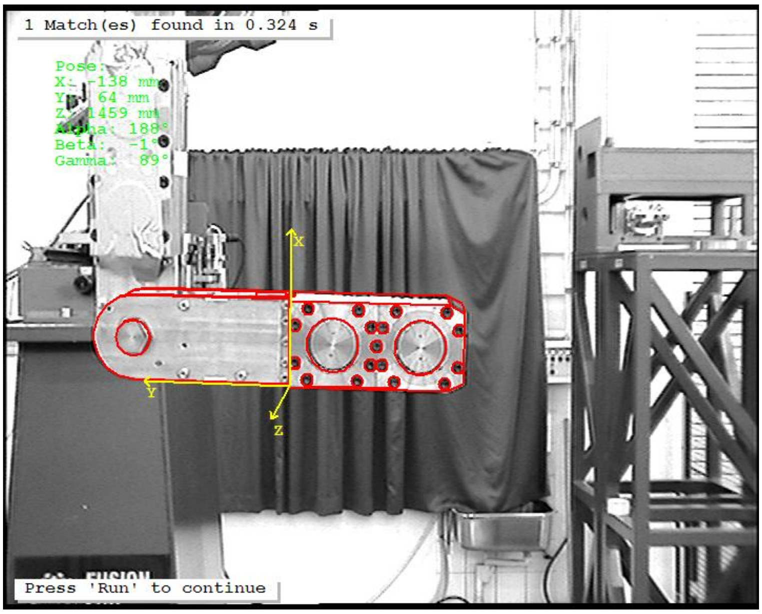

Figure 5-1*. The output of markerless AR process*

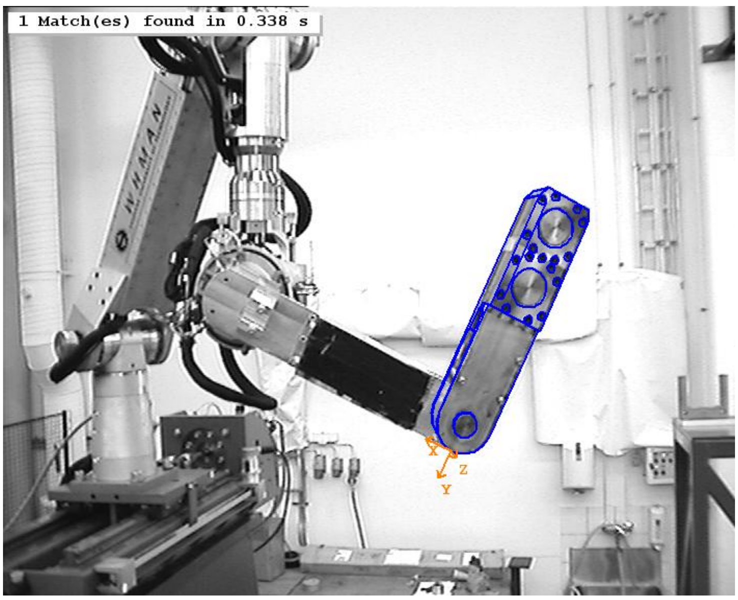

Figure 5-2. *AR with different gravity centre of Cad-model in the joint of the WHjack .*

The output display, projects the coordinate axis to the image and shows the pose include position (x, y, z) and orientation (α, β, γ) at the projected reference point consequently. The typical maximum time of tracking or finding the best match is 0.3 s. This projection presents a robust framework for 3D Cad-model based tracking of complex objects in unstructured environments. Figure 5.2 illustrates the markerless AR of WHjack in real RH environment.

5.1. Length Measurment Using AR

Depend on the measurement objectives the pose of the gravity center in the Cad-model can be changed. Two parallel augmentation processes takes a little time more than one-augmentation process but by using of two-augmentation process the length, measurement can be done. The most important features effects on the measurement using AR, are:

- The calibration procedure is a basic step to find relationship between real world and image coordinates
- The pinhole camera establishes a mathematical relationship between central projections of 3D object plane to 2D image plane
- The gravity center defines the pose of augmented Cad-model in respect to the camera center coordinates
- The definition of desired CG of the Cad-model depends on the objectives
- The gravity center position of the volume model, augmented in real model, will be found during AR.

Figure 5.3 shows the relationship between camera coordinates and CGs of two objects.

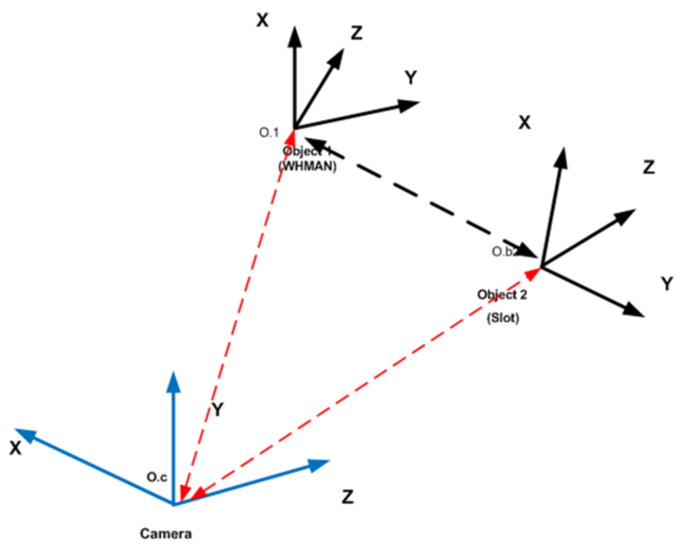

Figure 5-3. *The relationship between the camera center and gravity centers of objects*

The configuration of object in space can be determined by adding translation information to the rotation. If we use the $(\boldsymbol{X}_{O.c}, \boldsymbol{Y}_{O.c}, \boldsymbol{Z}_{O.c})$ coordinates of the camera origin, we have the below relations between the camera coordinates and two different gravity centers $(\boldsymbol{X}_{O.1}, \boldsymbol{Y}_{O.1}, \boldsymbol{Z}_{O.1})$ $(\boldsymbol{X}_{O.2}, \boldsymbol{Y}_{O.2}, \boldsymbol{Z}_{O.2})$ of two objects:

$$\boldsymbol{O_c O_1} = \sqrt[2]{(\boldsymbol{X}_{O.c} - \boldsymbol{X}_{O.1})^2 + (\boldsymbol{Y}_{O.c} - \boldsymbol{Y}_{O.1})^2 + (\boldsymbol{Z}_{O.c} - \boldsymbol{Z}_{O.1})^2} \qquad \text{(Eq 5.1)}$$

$$\boldsymbol{O_c O_2} = \sqrt[2]{(\boldsymbol{X}_{O.c} - \boldsymbol{X}_{O.2})^2 + (\boldsymbol{Y}_{O.c} - \boldsymbol{Y}_{O.2})^2 + (\boldsymbol{Z}_{O.c} - \boldsymbol{Z}_{O.2})^2} \qquad \text{(Eq 5.2)}$$

Then we have the measured length $(\boldsymbol{O_1 O_2})$:

$$\boldsymbol{O_1 O_2} = \sqrt[2]{(\boldsymbol{X}_{O.1} - \boldsymbol{X}_{O.2})^2 + (\boldsymbol{Y}_{O.1} - \boldsymbol{Y}_{O.2})^2 + (\boldsymbol{Z}_{O.1} - \boldsymbol{Z}_{O.2})^2} \qquad \text{(Eq 5.3)}$$

The measurement steps include:

1. tracking the gravity center 1 (CG1) (takes about 0.3 second)
2. tracking the gravity center 2 (CG2) (takes about 0.3 second)
3. augmentation of the both Cad-models
4. specifying the pose of CG1 and CG2 in respect to the camera
5. calculating the length $\boldsymbol{O_c O_1}$ and $\boldsymbol{O_c O_2}$ using the above formulation
6. both calculations are in respect to the camera center. Therefore, the length $\boldsymbol{O_1 O_2}$ can be found using the equations (5.3).

5.1.1. Evaluation 1

Each instance is capable for tracking the position and the orientation using the given 3D-model of desired object in online video stream. A matching score for each frame will be defined. Measure the lengths of WHjack with transformation and slight rotation using markerless AR were evaluated in this section.

The distance between WHjack and camera is about 1500 mm. Our length objective is between O1 and O2.

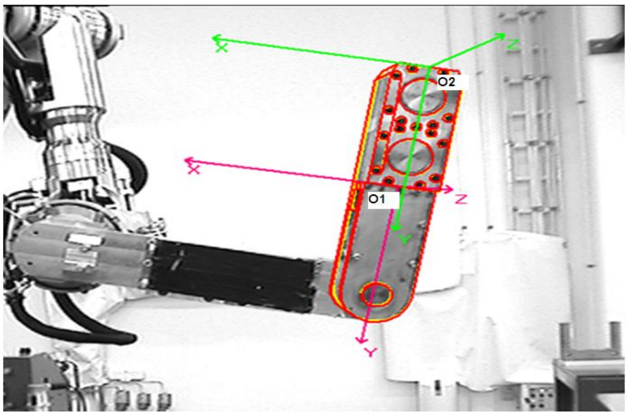

Figure 5-4. *The real length, between two points (O1, O2) is 23 cm.*

The coordinates of CG1 (O1) and CG2 (O2) are outputs of the AR process. The length between these two points (see Figure 5.4) can be obtained by using (Eq 5.3).

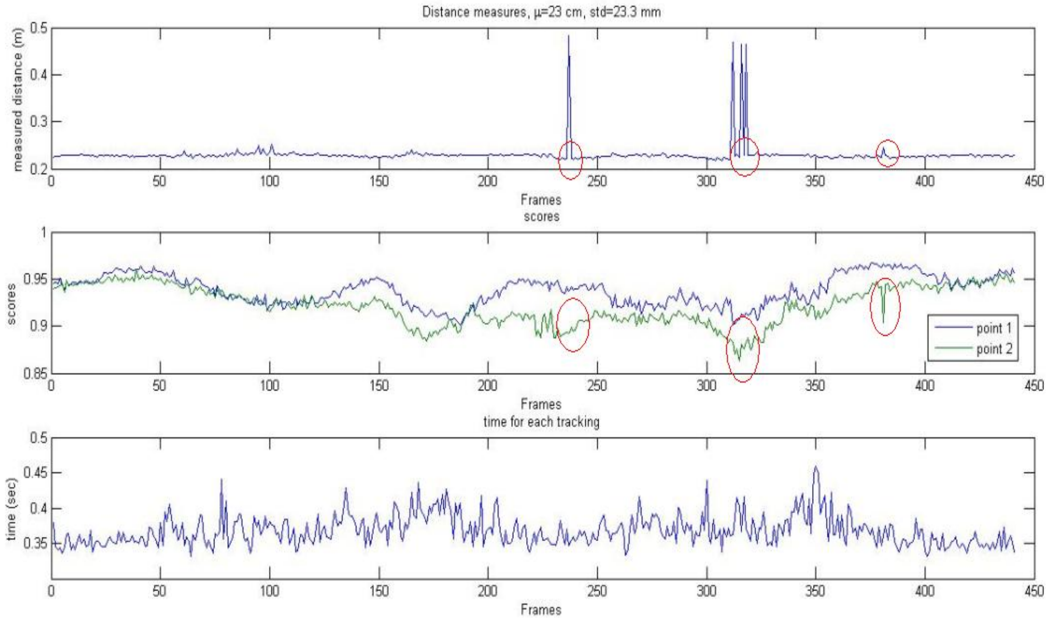

Figure 5-5*.Statistical data curves of AR length measurement.*

The real length is 23cm and the measured lengths via the AR process for 450 frames with transformation and slight rotation are plotted in Figure 5.5. The mean value of length measurement in real scene is $\mu = 23cm$ that is equal to the real length. The standard deviation (STD) is a statistic defining how tightly all the various frame results are clustered around the mean in a set of data. Here, the smaller is STD ($STD = 23.3\ mm$) and the reliable are measurements.

In the score curve results, red circles show the weak score-matching template. Weak scores of matching process in some tracks are because of bad matching in some frames. Therefore these weak score results can be omitted to increase the accuracy of length measurement.

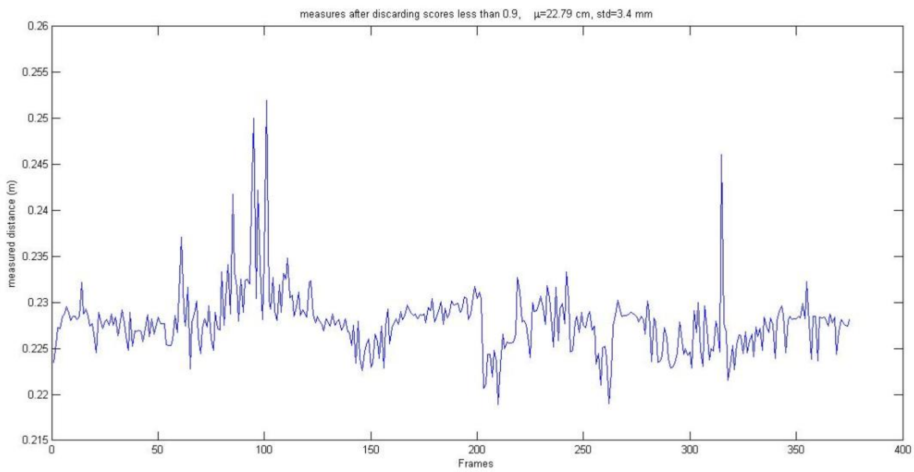

Figure 5-6. *Statistical data after discarding low score data (less than 0.9), for measuring the length (23cm)*

Figure 5.6 shows the statistical data after discarding the values less than score=0.9 for this length measurement.

By this we have the new $STD = 3.4\text{mm}$ and$\mu = 22.79$. The strong decrease in STD means that the results are now more reliable. The histogram of length measurement for 450 frames was plotted in Figure5.7. The histogram shows the almost Gaussian distribution of output measurement data via AR and real length of WHjack.

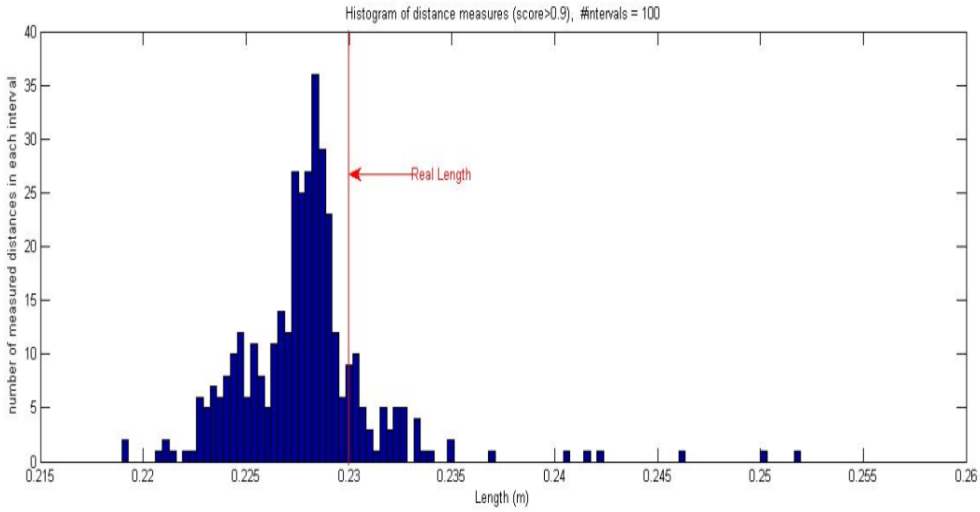

Figure 5-7.*The histogram of length measurement (23cm) by AR*

5.1.2. Evaluation 2

Here, the coordinates of CG1 (O1) and CG2 (O2) are output of the AR process. The length between these two points (see Figure 5.8) can be obtained by using (Eq 5.3). The real distance between WHjack and camera is about 1500 mm.

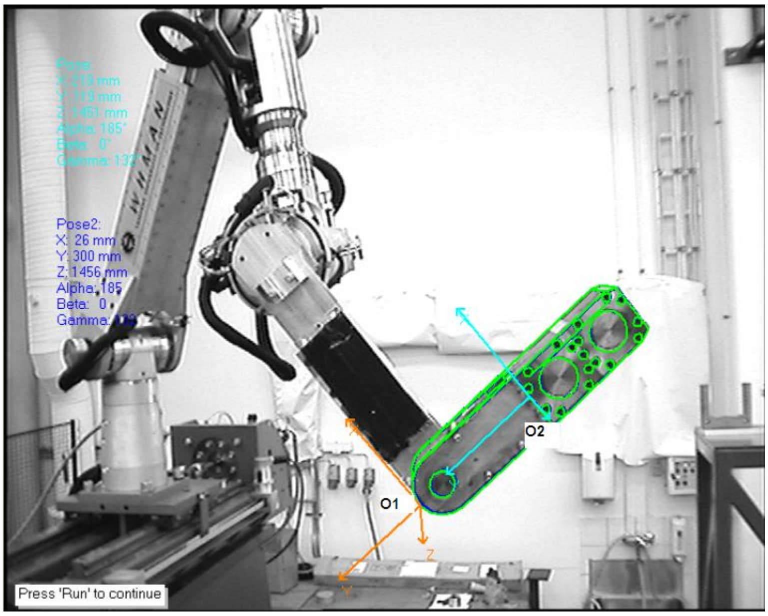

Figure5-8. *Measure the length between (O1, O2).*

The curved output data shows, the mean value is $\mu = 26.39$ and $\mathrm{STD} = 2.6\mathrm{mm}$. The curve result shows almost Gaussian distribution of data and reasonable standard deviation (see Figure 5.9).

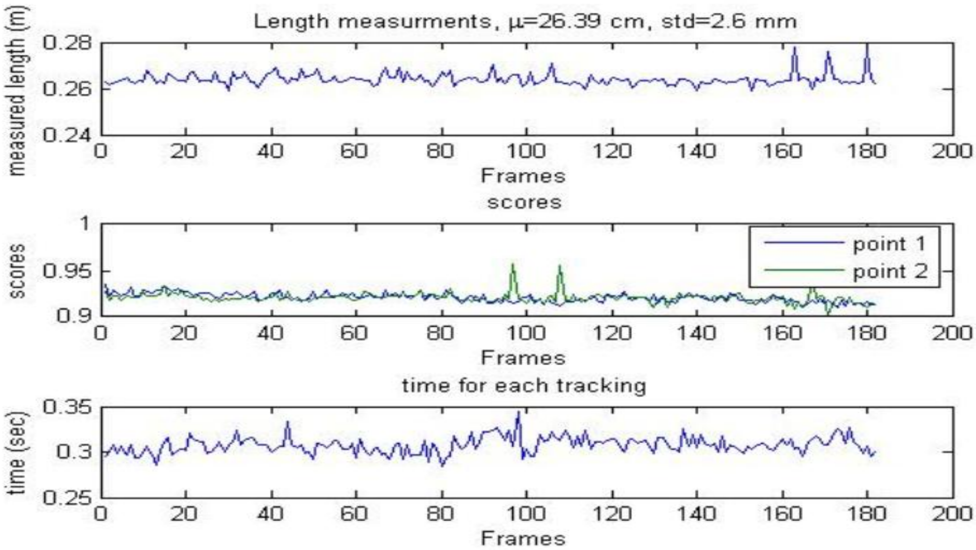

Figure 5-9. *Length measurement outputs of AR, with real length (26.5 cm) of WHjack*

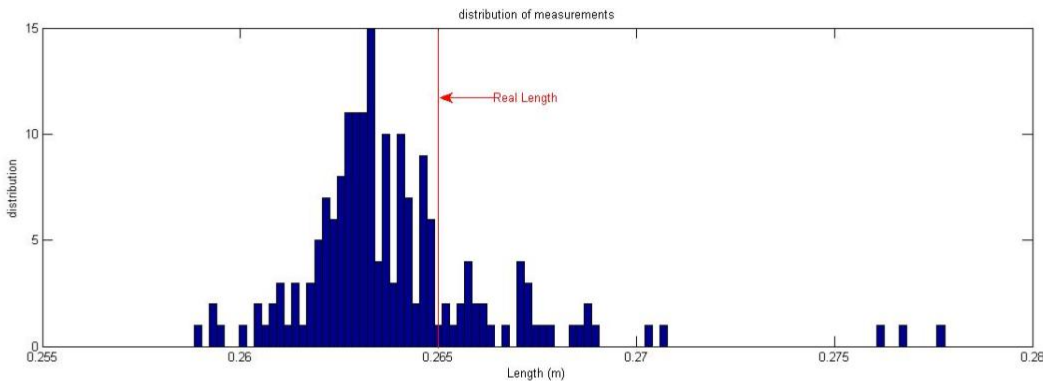

Figure 5-10. *The histogram of length (265mm) measurement using AR*

The histogram of output (see Figure 5.10) shows Gaussian distribution of length (265mm) measurements using AR process.

5.2. Distance Measurement

This part is evaluation of measured distances of markerless AR in laboratory with fixed object without motion and rotation. The AR process by no-motion WHjack is difficult, because finding the template matching for no-motion object is problematic. The outputs of calibration process are:

Focus= 0.00467588

Kappa= -8479.38

Sx = $5.88274e^{-006}$

Sy = $5.5e^{-006}$

Cx = 381.174
Cy = 287.856
Image Width = 720
Image Height = 576
The augmentation process was applied in 100 cm distance (see Figure 5.11) , between the camera and the WHjack in laboratory. The outputs of the Augmentaion process, even in weak illumination, had reasonable accuracy. The real distace was measured by conventional measuring method.

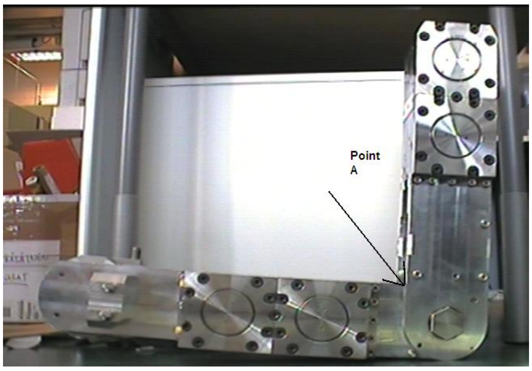

Figure 5-11. *Distance was measured by a tape measure from point A to the center of camera*

The (Eq 5.4) defines the length measurement relationship between camera center and gravity center of augmented Cad-model :
D: Measured via AR
R: Real distance from camera

$$\text{Measured distance } (D) = \sqrt{X^2 + Y^2 + Z^2}$$

$$\text{Accuracy}=|(R-D)/R| \qquad \text{(Eq 8.4)}$$

Accuracy$\times$ 100 shows calculated the percentage accuracy.

5.2.1. Evaluation

- **Output with R= 1000 mm**

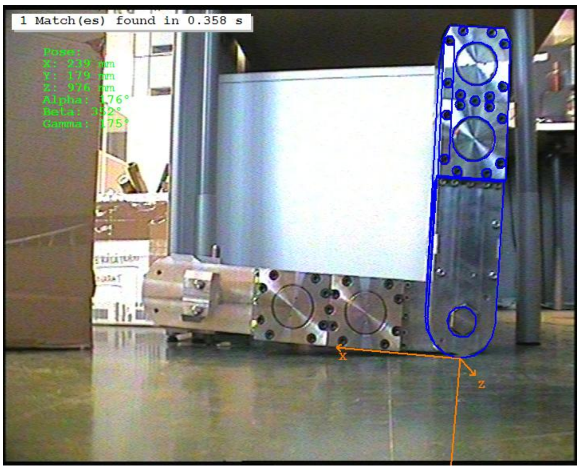

Figure 5-12. *One grabbed sequence gives D= 1019mm and Accuracy= 0.019*

- **Output with R= 1300 mm**

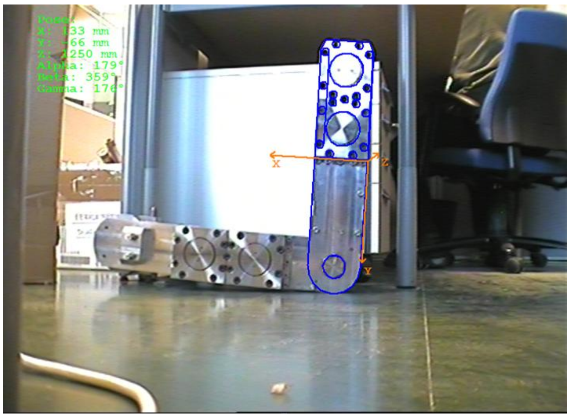

Figure 5-13. *One grabbed sequence gives D= 1259mm and Accuracy: 0.032*

- **Output with R=1500 mm**

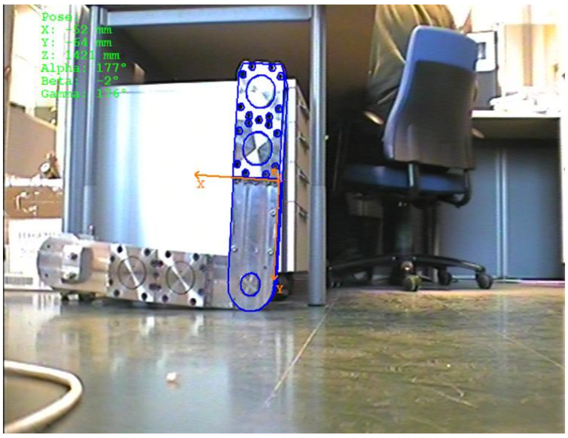

Figure 5-14. *One grabbed sequence gives D= 1423mm and Accuracy: 0.051*

- **Output with R= 2000 mm**

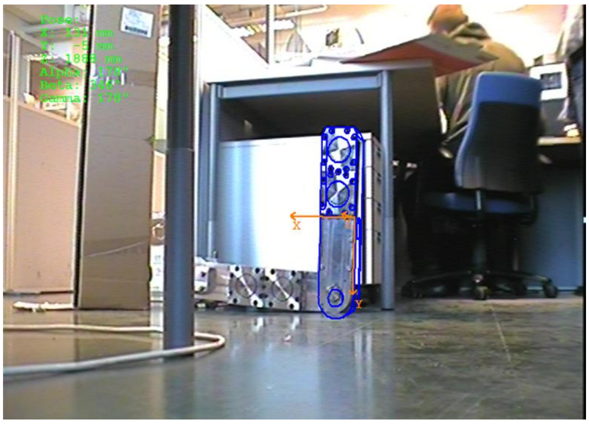

Figure 5-15. *One grabbed sequence gives D= 1888mm and Accuracy: 0.056*

5.2.2. Remarks

The real distances were measured in respect to the point A (see Figure 5.11). Data (transformation and orientation) of augmentation process was measured in respect to coordinate centre of the Cad-model. This coordinate centre was changed in some augmentation process (see Figure 5.16).
The accuracy in this evaluation process was considered in respect to the fixed real point (A). Actually, there are some small differences between these accuracies and real accuracy.

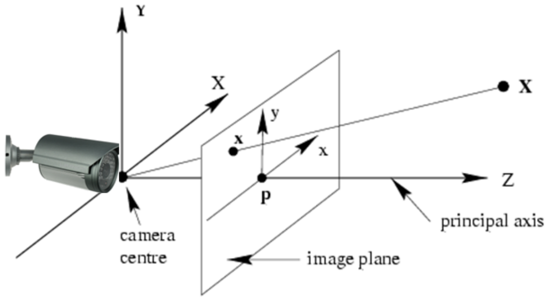

Figure 5-16*. The average distance from the focal point of camera to the centre point of the target*

5.2.3. Results

The results are illustrated in Figure 5.17. The accuracy is without unit and we can consider the accuracy using percent.

- The average accuracy (when R= 1000mm without rotation): 2%
- The average accuracy (when R= 1300mm without rotation): 3.3%
- The average accuracy (when R= 1500mm without rotation): 3.9%
- The average accuracy (when R= 2000mm without rotation): 5.6%

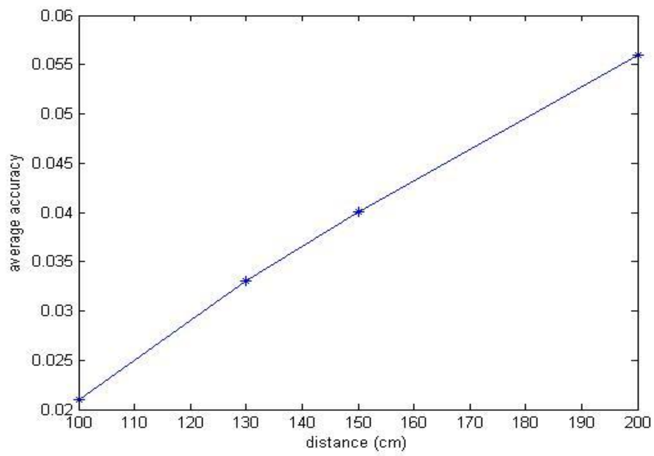

Figure 5-17*. Average accuracy versus average distance (cm)from camera.*

5.3. Measurement of Rotation

Markerless AR gives extra information about the rotation, transformation and orientation of the object.

In acquisition step, we can train the AR program to find the WHjack in different position and different orientations. Then, by using the already existing camera calibration data, accurate orientation can be determined (see Figure 5.18).

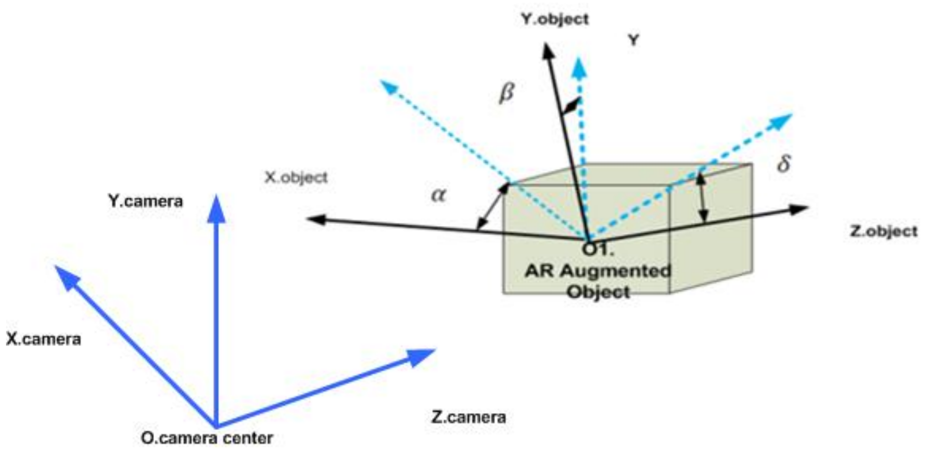

Figure 5-18. *Object orientation in respect to the camera coordinates.*

The gravity center pose of an augmented cad model can be specified continuously during the AR process.

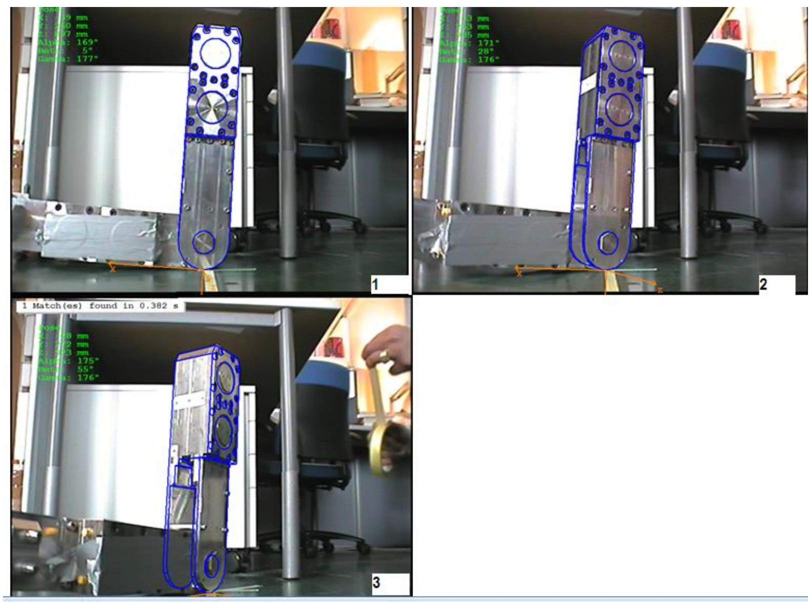

Figure 5-19. *Rotation measurement in three positions with different orientation*

The output data (x, y, z) and (α, β, δ) of the AR process determines the gravity center pose of the object. Data assist the operator as a useful feedback to calculate the rotation and orientation of the object, in respect to the fixed camera coordinates. The rotation measurement of WHjack was investigated in some frames (see Figure 5.19).

Real angle (measured manually) between positions of Whjack in Figure 5.19.2 in respect to its position in Figure 5.19.1 is about 34 degrees and real angle between positions of WHjack in Figure 5.19.3 in respect to position of Figure5.19.3 is about 65 degrees.

5.3.1. Evaluation

The measured data are:

- Position 1: Alpha = 169 degrees Beta = 5 degrees Gamma = 177 degrees
- Position 2: Alpha = 171degrees Beta = 28 degrees Gamma = 177 degrees
- Position 3: Alpha = 175 degrees Beta = 55 degrees Gamma = 176 degrees

The measured rotation of position 2 in respect to position1(See Figure 8.19), around the y-axis is 23 degrees and real rotation is about 34 degrees. The measured rotation of position 3 in respect to position 1 around the y-axis is 50 degrees and real angle is about 65 degrees. These measurement outputs were obtained from few frame numbers of the AR process. The results were repeated with small differences.

The result of length measurement using AR in two positions and rotations are illustrated in Figure 5.20 and Figure 5.21.

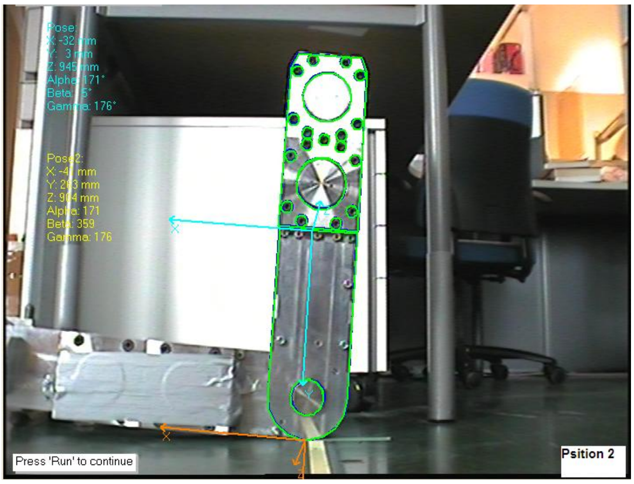

Figure 5-20. Measure the length, using AR

Real length in figure 5.20 is 265mm and measured length using AR is 262.193mm:

$$\sqrt{(32-4)^2+(3-263)^2+(945-964)^2}=262.193mm$$

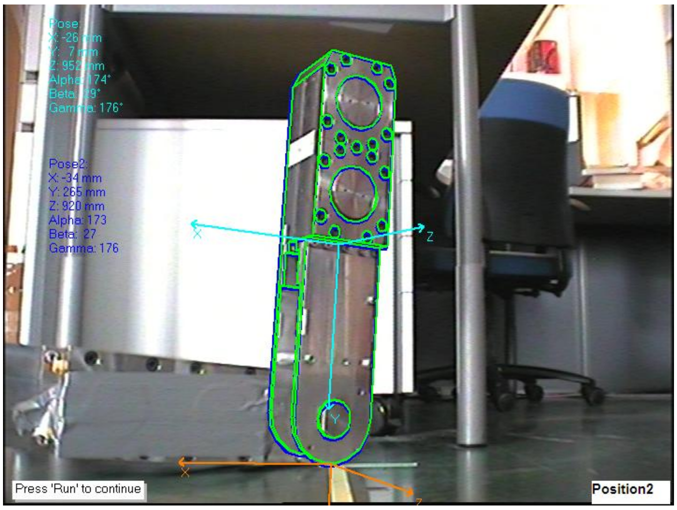

Figure 5.21. *Measure the length using AR (with rotation)*

Real length in Figure 5.21 is 265 mm with rotation and measured length using AR is 260.1mm:

$$\sqrt{(26-34)^2+(7-265)^2+(952-920)^2}=260.1mm$$

5.4. Optimization

To create a matching model, first a region of interest in the Cad-model covering the template in the training image process must be specified. Each model is manipulated via the handle. The created shape model is used for the shape based matching process.

If AR process gives the wrong tracking results or wrong augmentations, which are shown in Figure 5.21, how can we optimize the outcome of the AR process?

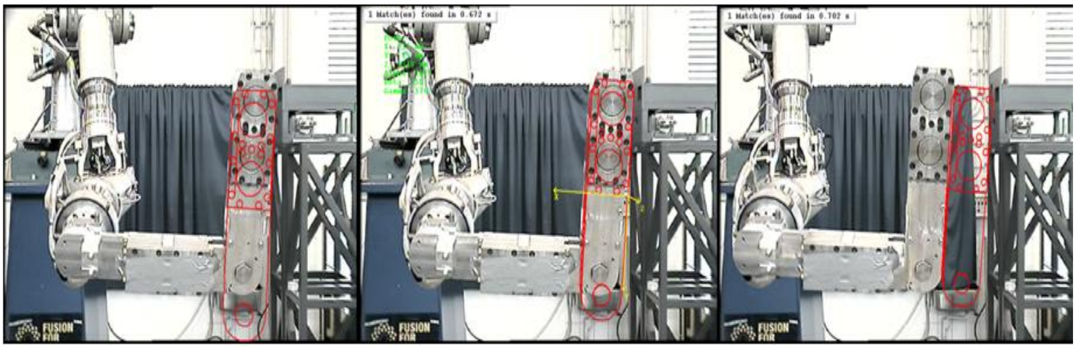

Figure 5-21. *Bad tracking and bad augmentation*

5.4.1. Optimizing the Outcome of AR Process

This example illustrates the WHjack-AR with slight rotation and displacement. During the manipulation process, if the manipulator goes out of the distance used during the training process, it will cause a wrong tracking result and wrong augmentation. Therefore, it is important to train most of the positions, which are used during the manipulation process.

The parameters used for creation of shape model application are dependent and must be always specified when creating a 3D shape model. In addition, some generic parameters can optionally be used to influence the model creation. For most applications, these parameters do not need to be specified but can be left at their default values. Selecting the unrealistic parameters via this operator may cause wrong. Therefore, the best settings for the camera parameters essentially determine the level of tracking and augmentation.
In addition, there are some bugs during this AR implementation, for the WHjack as a case study, which sometimes cause a bad tracking and wrong augmentation.
These found bugs include:

1. We know the calibration process includes some steps. The setting of the initial parameters is the first step of calibration process (see page 19). Here the initial camera parameter (S_x=0.5$\times 10^{-6}$) which imported as an input in the calibration process is value for camera lens (1/3"-chip) but the camera lens was used in this project is (1/4"-color), (see appendix C). In other words width of a cell chip, on our CCD was used wrongly because our used camera lens width was not already defined by Halcon
2. During the calibration process, the calibration plate should fill at least a quarter of the whole image to ensure the robust detection of the marks. However, this condition was not observed during our calibration process

5.4.2. Proposed Camera

The task is a basis for the major decision related to the camera characteristics that had to be made for design. This proposed camera will give the measurement accuracy about 1 mm or less in our desired FOV (see Figure 5.22).
In other words, this chapter gives optimum camera information in AR system [see calculation in Appendix B] [19].

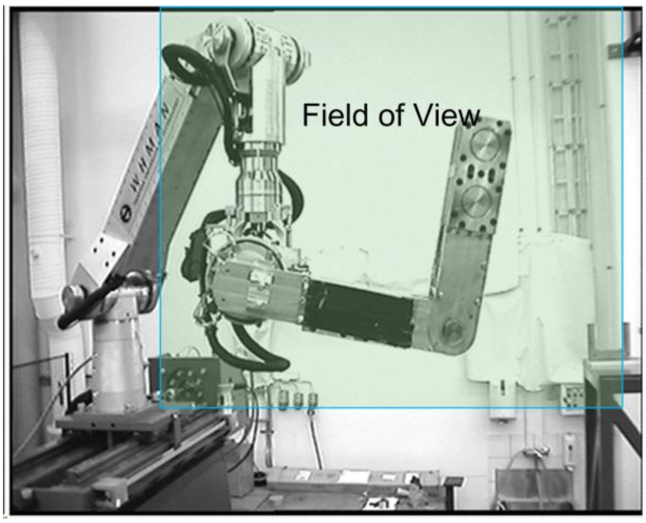

***Figure 5-22**. The desired field of view (FOV)*

A successful design is based on detailed specification also the task and the environment are needed to be described. It is essential to cover error free in the range between just good and required acquired resolution. Table 5.1 defines the proposed camera by considering the required resolution.

The most important RH-ITER environment features which have to be checked due to proposed camera are as follows:

- Ambient light
- Dirt or dust that the equipments need to be protected from them
- Shock or vibration
- Hot or cold
- Due to the large gamma radioactivity flux in RH-ITER, the conventional imaging component cannot be successfully used. High temperature, high magnetic field up to six Tesla, high gamma radiation Flux (1.5 kGy/h) and Dose (2.5 MG) are limiting factors [19] [See more in Appendix B].

Table 5-1 *AR_ITER proposed Camera*

Camera parameters	Demand	Wish
Sensor size	Depending on lens type	8.8mm-2/3"
Focal length	Variable (4mm -73mm)	12mm focal length
Type of camera	Non –telecenteric IST_REES R981/C981	
Distance from camera	1500mm	1500mm-2000mm
Field of view (FOV)	$1000mm \times 1000$mm	$1300mm \times 1300$mm
Special resolution	1.5mm/pix	1mm/pix
Resolution	720pix × 560pix	1000pix × 1333pix
Radiation tolerance	1MG[60 Co](H2O); 10^8Rad[60 Co](H20)	
Operating temperature ambient	Max 0^0C to 50^0	

6. ONGOING AND FUTURE WORK

AR in ITER-RH can help the operator to control the motion of WHjack. The ongoing objectives for the case study (WHjack) are as follows.

6.1. WHjack Insertion

The future objectives are as follows:

- Recognize and locate both object1 (WHjack) and object2 (Slot), using the template-matching algorithm in markerless setting (see Figure 6.1)
- Determine and display the location and orientation of the objects in three-dimensional workspace.
- Immediate AR feedback to assist operator for control action of system in near real-time. The maximum delay for the two tracking processes together is at least is 0.5 second.
- Reorganize and locate of the three markerless objects during three corresponding tracking processes (see Figure 6.2).

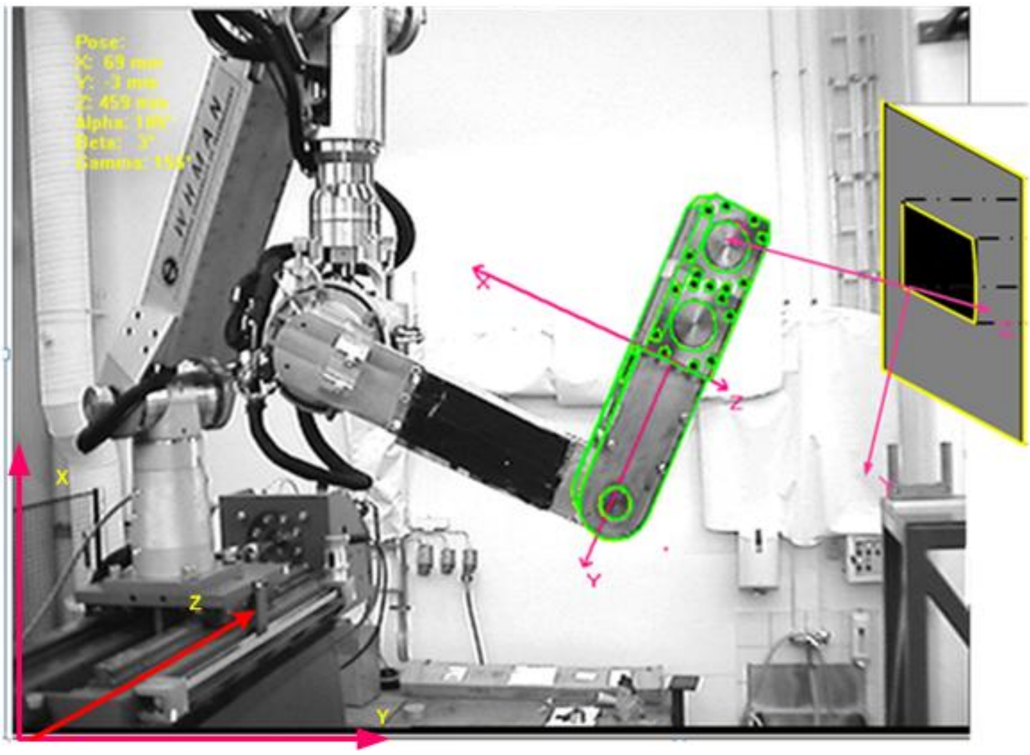

Figure 6-1. *Two markerless objects (WHjack and slot) via AR in RH scene*

The tracking time is a crucial point but there are some methods to decrease the time of tracking, for example modification the camera and other equipment.

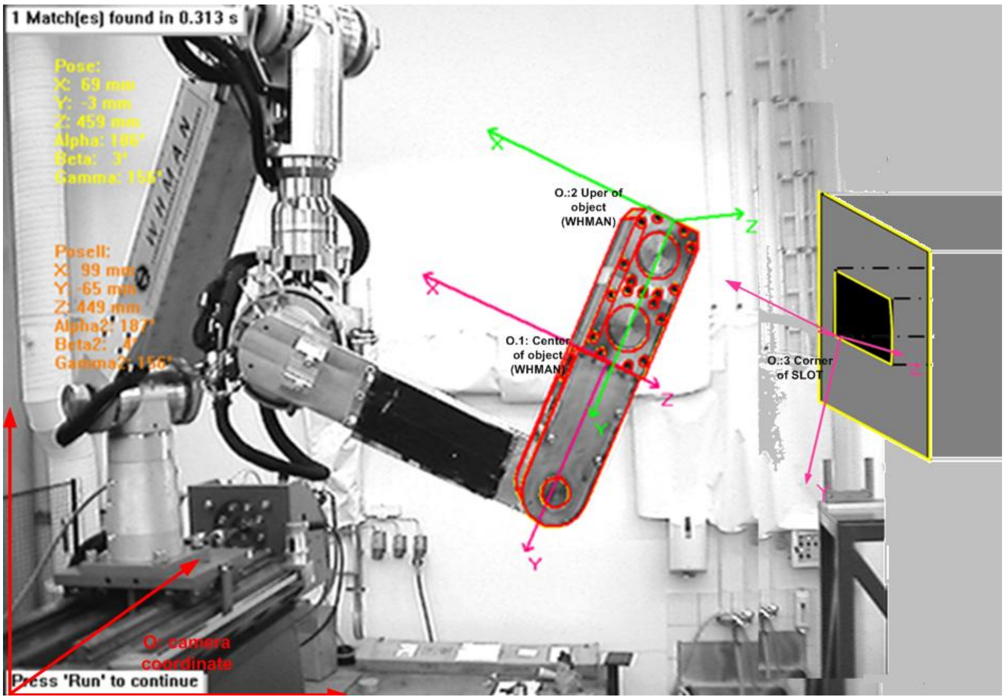

Figure 6-2. *Three markerless objects augmentation via AR process*

Additionally modifying and simplifying the Cad-model of an object can help to decrease the time of tracking.

Markerless AR with two or three objects in RH environment can help to find and display the desired gravity center of two or three objects in time of about 0.5 second also it determines the location and orientation of the objects. Measurement functions calculation can control the action of WHjack pose in respect to the pose of the slot hole.

6.2. Whjack control

If the augmentation process is enough accurate, the distance between two gravity centers of two objects using the (Eq 6.1) can be calculated. Actually when these two points coincides each other, the manipulator can enter the slot in ITER-RH process. In other words, the WHjack is accurately in front of the slot hole.

In addition, these two points are coinciding, if the rotation and position of both points is the same. The CG coordinates ($\boldsymbol{X_{O.W}}, \boldsymbol{Y_{O.W}}, \boldsymbol{Z_{O.W}}$) of WHjack and CG coordinates ($\boldsymbol{X_{O.H}}, \boldsymbol{Y_{O.H}}, \boldsymbol{Z_{O.H}}$) of slot hole are illustrated in Figure 6.3. These two points coincide if the length between them is zero.

$$\boldsymbol{O_{.W}O_{.H}} = \sqrt[2]{(\boldsymbol{X_{O.W}} - \boldsymbol{X_{O.H}})^2 + (\boldsymbol{Y_{O.W}} - \boldsymbol{Y_{O.H}})^2 + (\boldsymbol{Z_{O.W}} - \boldsymbol{Z_{O.H}})^2} \qquad \textbf{(Eq 6.1)}$$

$$\textbf{If } \boldsymbol{O_{.W}O_{.H}} = \boldsymbol{0}$$

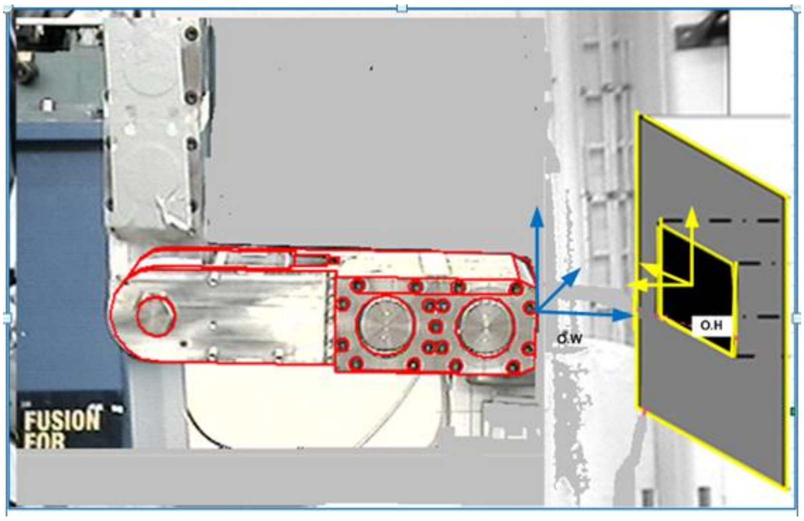

***Figure 6-3.** Tow center points ($\boldsymbol{O}_{.H}$, $\boldsymbol{O}_{.w}$) should be coincide*

Depending on the initial definition of the CG orientations of two points $O_{.H}: (\alpha, \beta, \delta)$ and $O_{.w}: (\alpha', \beta', \delta')$, the operator can estimate the WHjack orientation in respect to the slot gravity center.

The goal in ITER project is to use the markerless AR for specifying the rotation and transformation as an immediate feedback to control WHjack motion.

The proposed steps include:

- Specifying the orientation of the WHjack via AR augmentation
- Markerless AR gives position (x, y, z) and orientation (α, β, δ) of gravity center of Augmented WHjack. The orientation and rotation were defined in respect to camera coordinate center that was calibrated via calibration process
- The fixed camera origin will be transformed to the fixed manipulator body origin
- The rotation angle of an object in respect to the camera origin will be translated to the rotation angle in respect to the manipulator body origin
- The translated rotation as an AR redundant info can assist the operator directly.

Example:

The length O_1O_2(see Figure 6.4) can be changed during the manipulation process. The length of O_1O_2 when we have the camera origin $O_C(\boldsymbol{X_{O.c}}, \boldsymbol{Y_{O.c}}. \boldsymbol{Z_{O.c}})$, is calculated using these formulas:

$$\boldsymbol{O_cO_1} = \sqrt[2]{(\boldsymbol{X_{O.c}} - \boldsymbol{X_{O.1}})^2 + (\boldsymbol{Y_{O.c}} - \boldsymbol{Y_{O.1}})^2 + (\boldsymbol{Z_{O.c}} - \boldsymbol{Z_{O.1}})^2} \quad \textbf{(Eq 6.2)}$$

$$\boldsymbol{O_cO_2} = \sqrt[2]{(\boldsymbol{X_{O.c}} - \boldsymbol{X_{O.2}})^2 + (\boldsymbol{Y_{O.c}} - \boldsymbol{Y_{O.2}})^2 + (\boldsymbol{Z_{O.c}} - \boldsymbol{Z_{O.2}})^2} \quad \textbf{(Eq 6.3)}$$

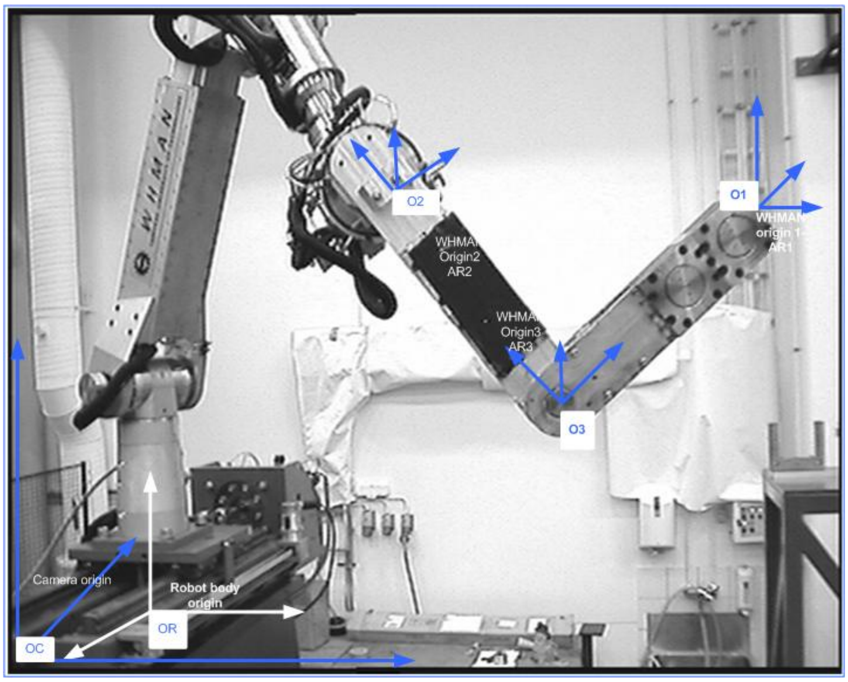

Figure 6-4. *Measuring the rotation and orientation of objects using AR in respect to the WHMAN body-origin*

If the camera center is O_C : $(\boldsymbol{X_{O.c}}, \boldsymbol{Y_{O.c}}.\boldsymbol{Z_{O.c}})$ and manipulator body center is O_R: $(\boldsymbol{X_{O.R}}, \boldsymbol{Y_{O.R}}.\boldsymbol{Z_{O.R}})$, then the position of the camera in respect to the manipulator body originO_R is:

$$\left((\boldsymbol{X_{O.C}} - \boldsymbol{X_{O.R}}\ ), (\boldsymbol{Y_{O.C}} - \boldsymbol{Y_{O.R}}), (\boldsymbol{Z_{O.C}} - \boldsymbol{Z_{O.R}})\right)$$

Therefore, the lengths measurement in respect to the manipulator body centers is:

$$\boldsymbol{O_R O_2} = \sqrt[2]{\left((\boldsymbol{X_{O.C}} - \boldsymbol{X_{O.R}}\ ) - \boldsymbol{X_{O.2}}\right)^2 + \left((\boldsymbol{Y_{O.C}} - \boldsymbol{Y_{O.R}}) - \boldsymbol{Y_{O.2}}\right)^2 + \left((\boldsymbol{Z_{O.C}} - \boldsymbol{Z_{O.R}}) - \boldsymbol{Z_{O.2}}\right)^2} \quad \textbf{(Eq 6.4)}$$

$$\boldsymbol{O_R O_1} = \sqrt[2]{\left((\boldsymbol{X_{O.C}} - \boldsymbol{X_{O.R}}\ ) - \boldsymbol{X_{O.1}}\right)^2 + \left((\boldsymbol{Y_{O.C}} - \boldsymbol{Y_{O.R}}) - \boldsymbol{Y_{O.1}}\right)^2 + \left((\boldsymbol{Z_{O.R}} - \boldsymbol{Z_{O.C}}) - \boldsymbol{Z_{O.1}}\right)^2} \quad \textbf{(Eq 6.5)}$$

The next goal related the RH project is to specify the joint angle between two parts of the manipulator. This goal is explained in these following steps:

- Specifying the orientation of two parts of a WHjack connected with joint via AR
- Markerless AR give position (x, y, z) and orientation (α, β, δ) of gravity centers of two augmented objects using AR
- The orientations and rotations are defined in respect to the camera center that is calibrated via the calibration process
- Specifying the angle between two parts of arm via specifying the gravity center-orientation of both object using AR process

6.3. AR via Occluded View

Another goal of AR process is to find the object in images even if it is occluded or disturbed, or some part of the object is missed. Furthermore, the object should be found even if there are large numbers of disturbance on the object itself, or if there are severe nonlinear illumination changes.

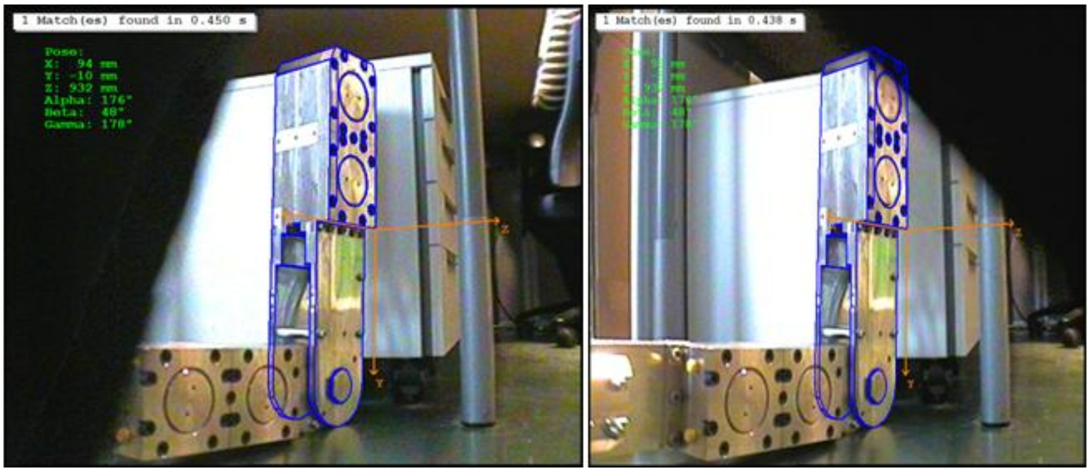

Figure 6-5. *Occluded some part of view*

Due to find the WHjack even if some parts are in hole, the results shows the reasonable tracking even if 15% of object is occluded (see Figure 6.5 and Figure 6.6).

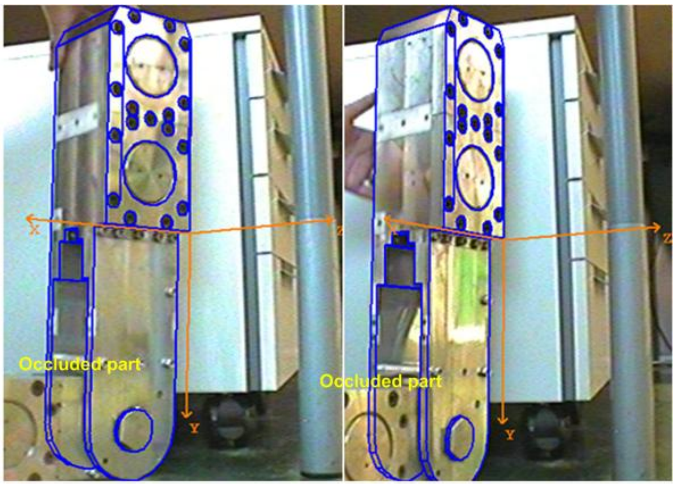

Figure 6-6. *Display the occluded part of WHjack using AR*

Also during the manipulation process, when WHjack will be occluded in slot hole and the user cannot directly track it, the AR process can assist the operator to find the accurate pose of the WHjack (see Figure 6.7). It is essential for any AR application to provide an augmented display that is easy to interpret by the user.

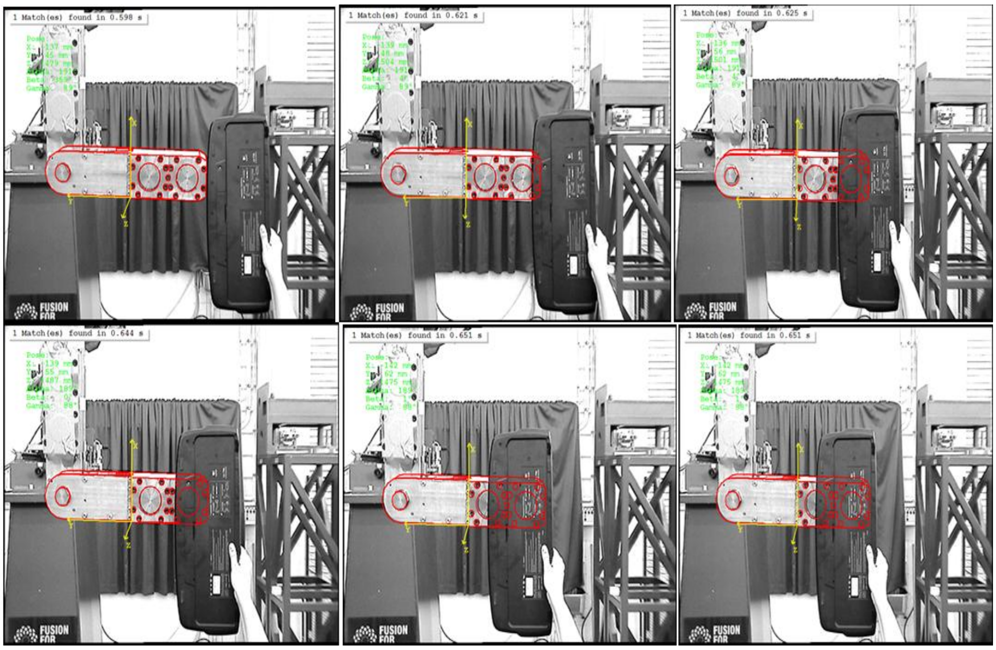

Figure 6-7. *AR via occluded (5% to 40%) views of WHjack*

A significant visual cue for understanding the spatial relationships in a scene is the correct occlusion of objects from the user’s viewpoint. The future goal is having a high percentage of the camera's view occluded or a full-occluded view is impossible to keep tracking.

7. CONCLUSION

In this thesis, the markerless AR interface was successfully developed in RH environment using the shape-based matching algorithm to assist the operator as a visual feedback.

It was demonstrated that it is possible to augment the 3D Cad-model of a physical object (WHjack) without exploiting any marker for detecting the object and use it for remote handling in the ITER project.

The performance of the AR-RH system depends on hardware equipments (camera, illumination condition, etc) as well as software procedures (calibration method, object-recognition algorithm) utilized for implementing the system. The AR process produced a virtual environment that was superimposed on a visible or occluded user's view. This superimposed 3D Cad-model additionally specifies the measured values of orientation and transformation of markerless WHjack, in near real-time tracking. The pose (position and orientation) of augmented 3D Cad-model was consequently displayed in the user's view.

It was shown the AR-RH assist the operator to remotely handle the functions needed in the ITER environment, which due to health or physical consideration is not directly accessible by human. The methods in this thesis were validated in the RH-ITER mock-up scene and proven to be robust enough.

The ongoing objectives related RH-ITER includes WHjack control and insertion in visible or occluded views, can help the operator to control the WHjack action in more safe and more efficient condition.

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APPENDIC A: SPECIFYING A USEFUL CAMERA

Specifying a Camera for ITER Remote Handling, using AR

This chapter explains how to design a camera characteristics in AR-ITER. The detailed descriptions are about different terms such as camera characteristics and application components regarding the machine vision system in RH-AR-ITER.
Now, this section focuses to concrete vision task and the solution that provides a basis for the major decisions
Critical steps for design are:

- choosing the camera type
- determining the field of view
- calculating resolution
- choosing a lens
- selecting a camera model ,frame-grabber and hardware platform
- addressing aspect of mechanical and electrical interface
- designing and choosing a software

Camera performance Requirements

The performance requirement can be seen in the aspect of:

- Accuracy
- Time performance

Accuracy

The defined accuracy is 1 millimeter in measuring as it influences the required resolution.

Time Performance

The vision system is one link in RH-ITER, its task has to be finished within a specified time. The requirements regarding processing time will influence the choice of the hardware platform (WHMAN application) and will eventually use certain algorithms (Template matching).
The following times specify the time performance.

- Start of acquisition
- Maximum processing (tracking and augmentation) time

Camera Type

Choosing the area-camera is fundamental decision for the design. The Telecentic or non- Telecentregion is another camera characteristics .It is clear the type of camera in should be non-Telecentric model.

Telecentric and Non-Telecentric Camera model

Field of View

The field of view in this project is determined by the following factors

- Maximum WHjack size is (50 cm *67cm)
- Maximum variation of WHjack presentation in translation and orientation was defined by application of WHjack.
- The field of view in RH-ITER is about 100 cm*100cm

Resolution

- Camera sensor resolution
- Spatial resolution
- measured accuracy

Camera Sensor Resolution

The numbers of columns and rows that a camera provides are specified by the internal sensor. It is measured in pixels. Besides the number of pixels, the size of one pixel- the cell size-is required for the lens design.

Special Resolution

The spatial resolution is a matter of direct mapping of real-world objects to the image sensor. It can be measured in mm/pixel. This resolution depends on the camera sensor and the field of view. The mapping is done by lens. Some area cameras do not provide square pixels so that the resulting spatial resolution is not equal in horizontal and vertical direction.

Measurement Accuracy

Depending on the software algorithm, the measurement accuracy can be different from the spatial resolution. The following table presents an overview of algorithms and accuracy that can be expected.

Algorithm	Accuracy in pixel
Edge detection	1/3
Pattern matching	1

The spatial resolution is necessary to achieve a measurement accuracy depends on the feature contrast and software algorithm.

Calculation of Resolution

For choosing a camera model, the required resolution has to be determined. Therefore, the size of the smallest feature that has to be inspected and the number of pixels to map this feature are crucial.

Name	Variable	Unit
Camera resolution	R_c	pixel
Spatial resolution	R_s	mm/pixel
Field of view	FOV	mm
Size of the smallest feature	S_f	mm
Number of pixels to map the smallest feature	N_f	pixel

$$\mathrm{R_c} = \mathrm{FOV} / \mathrm{R_S}$$

$$\mathrm{R_s} = \mathrm{S_f}/\mathrm{N_f}$$

Pixel Rate

The Pixel Rate (PR) is the speed of imaging in terms of pixels per second.

$$\mathrm{PR} = R_{C-hor} \cdot R_{C-ver} \cdot f_r + \text{overhead.}$$

Name	Unit
Pixel rate (PR)	pixel/s
Camera resolution horizontal(R_{C-hor})	pixel
Camera resolution vertical (R_{C-ver})	pixel
Frame rate (f_r)	Hz
Camera resolution($\mathrm{R_c}$)	pixel
Line frequency(f_s)	Hz

Overhead should be consider about 10% to 20%

Lens Characteristic

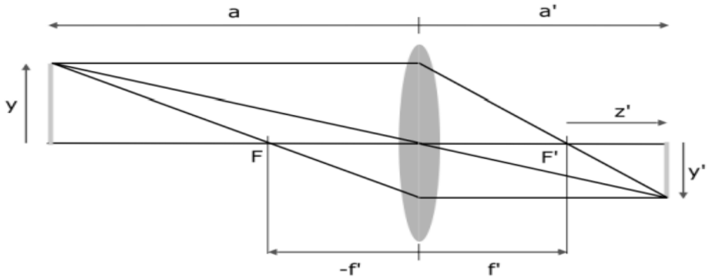
An important parameter for the lens design is the standoff distance. In general, using greater distances will increase the image quality. The available space should be used to obtain an appropriate standoff distance. This distance is used to calculate the focal length.

Focal Length

A real world object with the size y is mapped by the lens to an image object of the size y'.

$$\frac{1}{f'} = \frac{1}{a'} - \frac{1}{a}$$

$$\beta = \frac{y'}{y} = \frac{a'}{a} \quad .$$

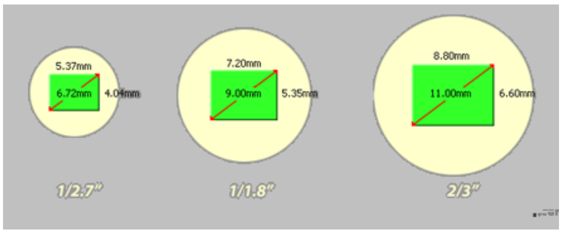


$$\beta = -\frac{\text{sensor size}}{\text{FOV}} \quad .$$

$$f' = a \cdot \frac{\beta}{1-\beta}$$

Sensor Size

The sensor size is categorized in size 1/3``, 1/2``, 2/3`` and 1``.The size determines that a sensor lies within a circle of the named diameter. There is no specific mathematical relationship between the diameter of the imaging circle and the sensor size, although it is always roughly two thirds.

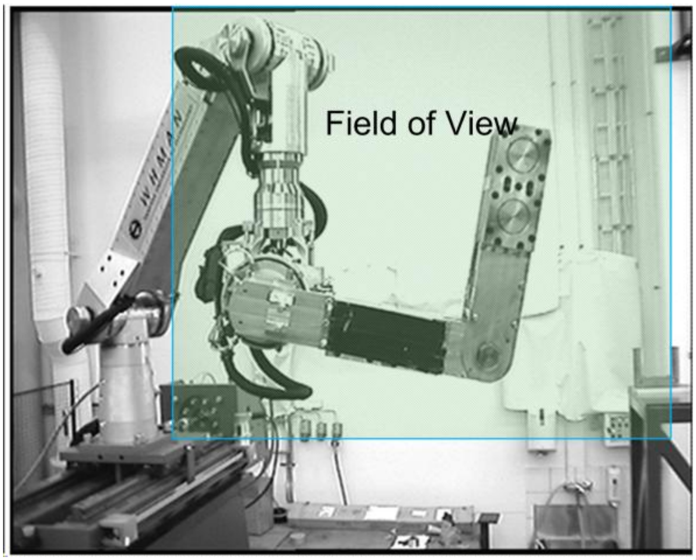


Size	Width (mm)	Height (mm)	Diagonal (mm)
1"	12.7	9.525	15.875
2/3"	8.8	6.6	10.991
1/2"	6.4	4.8	8.0
1/3"	4.8	3.6	6.0

Sensor size classification

Task

The task is selecting the camera to give the measurement accuracy about 1 mm or less in our desired FOV.



The desired FOV of AR_ITER

The requirement parameter for selecting the camera

	FOV	S_f	N_f	$\mathbf{R_s = S_f/N_f}$	$\mathbf{R_c = FOV/R_S}$	**Distance from camera**
Data 1	$1000mm \times$ 1000mm	1mm	1 pixel	1mm/pix	$1000p \times 1000p$	1500mm
Data2	$900mm \times 900mm$	1mm	5 pixel	0.2mm/pix	$4500p \times 4500p$	1000mm
Data3	$700mm \times 700mm$	1mm	10 pixel	0.1mm/pix	$7000p \times 7000p$	1000mm
Directshow interface –maximum resolution					$700p \times 560p$	

The aspect ratio of the camera usually is 4:3 and the field of view in horizontal and vertical is difference.

- FOV-Vertical:1000
- FOV-Horizontal ($1000\times4/3$):1333mm

- The FOV=1000mm×1333mm
- The resolution values for different conditions are illustrated in table.
- The frame grabber is Directshow and It gives the maximum resolution RGB (720*560)

Lens Design Task

The magnification can be calculated as:

$$\beta = -\text{sensor size}/\text{FOV}$$

W	Distance from camera	$R_c = FOV / R_S$	$\beta = -$sensor size/FOV Sensor size=8.8mm-2/3``	$\beta = -$sensor size/FOV Sensor size=6.4mm-1/2``
Data1	1500mm	$1000p \times 1000p$	$-\frac{8.8}{1000} = -8.8 \times 10^{-3}$	$-\frac{6.4}{1000} = -6.4 \times 10^{-3}$
Data2	1000mm	$4500p \times 4500p$	$-\frac{8.8}{900} = -9.78 \times 10^{-3}$	$-\frac{6.4}{900} = -7.11 \times 10^{-3}$
Data 3	1000mm	$7000p \times 7000p$	$\frac{8.8}{700} = -0.013$	$\frac{6.4}{700} = -9.143 \times 10^{-3}$

$R_s = S_f/N_f$	Distance from camera	$f' = \alpha \times (\beta)/(1-\beta)$ Focal length Sensor size=8.8mm-2/3``	$f' = \alpha \times (\beta)/(1-\beta)$ Focal length Sensor size=6.4mm-1/2``
1mm/pix	1500mm	$-1500 \times \frac{-(8.8 \times 10^{-3})}{(1 + 8.8 \times 10^{-3})} = 13.08mm$	$-1500 \times \frac{-(6.4 \times 10^{-3})}{(1 + 6.4 \times 10^{-3})} = 9.53mm$
0.2mm/pix	1000mm	$-1000 \times \frac{-(9.78 \times 10^{-3})}{(1 + 9.78 \times 10^{-3})} = 9.68mm$	$-1000 \times \frac{-(7.11 \times 10^{-3})}{(1 + 7.11 \times 10^{-3})} = 7.06mm$
0.1mm/pix	1000mm	$-1000 \times \frac{-(0.013)}{(1 + 0.013)} = 12.8mm$	$-1000 \times \frac{-(9.143 \times 10^{-3})}{(1 + 9.143 \times 10^{-3})} = 9.06mm$

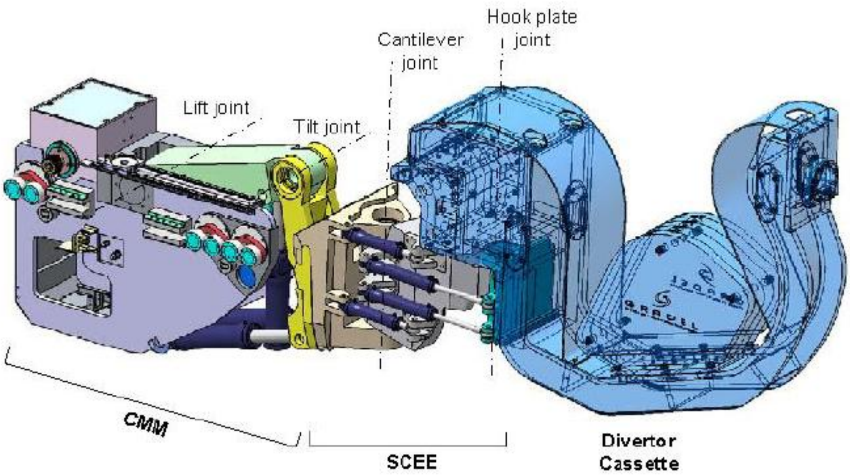
Remarks

The maximum Resolution supported by Directshow interface is 720×560, therefore the maximum special resolution provided by Directshow interface and calculated special resolution are:

Real resolution	Directshow interface Special resolution Horizontal $R_s = FOV / R_c$	Calculated Special resolution Horizontal (wish)
Data1	$\frac{1000}{720} = 1.38mm/pix$	1mm/pix
Data2	$\frac{900}{720} = 1.25mm/pix$	0.2mm/pix
Data3	$\frac{700}{720} = 0.972mm/pix$	0.1mm/pix

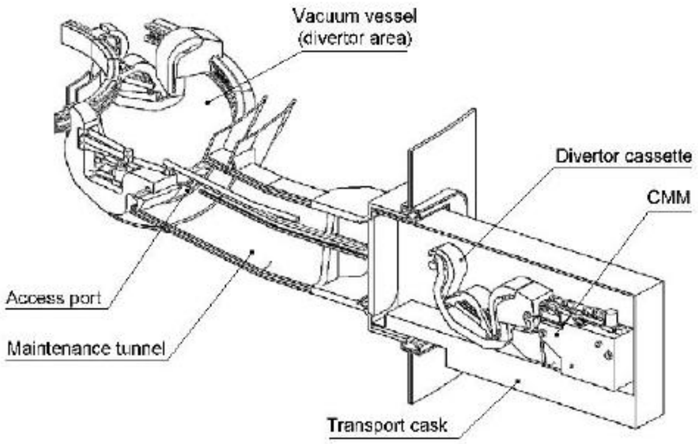
APPENDIX B: CMM

“The Institute of Hydraulics and Automation (IHA), at the Tampere University of Technology, has played an active role in the European FUSION program since 1994. IHA and the European Fusion Development Agreement (EFDA) have been participating in the design of the Divertor cassette mover, the so-called Multi-functional Cassette Mover (CMM). The CMM is a robotic device consisting of a main body and an articulated two-link mechanism (see bellow Figure). The main body travels in radial motion on the top of the maintenance tunnel rails. CMM radial motion is powered by two electrical servomotors driving two sets of rack-and-pinion systems. A resolver, integrated in the radial drive housing of the CMM body, can determine the radial position with an accuracy of 2 mm. The articulated mechanism of the CMM provides lifting and tilting motion to the Divertor cassette in the vertical plane”[20].



CMM/SCEE-Mover transporting a Divertor Cassette

ITER reactor chamber contains thousands of in-vessel components, from which the Divertor region constitutes the largest system. The Divertor occupies the lower part of the D-shaped plasma chamber, and it is segmented into 54 independents modular cassettes, mounted on two concentric in-vessel rails. The main function of the Divertor system is to exhaust the major part of the alpha particle power, helium and impurities from the plasma [20,22].



Schematic of Divertor maintenance area and device

APPENDIX C: CAMERA (ZB451IR/AF)

ZB5451IR/AF

Mid Range True Day/Night Bullet Style IR Camera

TECHNICAL SPECIFICATION

Model Number	ZB5451IR/AF
Image Sensor	Sony 1/4" Colour Super HAD CCD
Horizontal Resolution	500 TVL (Col) 570 TVL (Mono)
Lens	10x Optical (3.8-38mm Zoom Lens with Auto Focus) @ F1.8
No. Of LEDs	30 IR LEDs
Sensitivity (F1.8)	0.7 Lux (Day) 0 Lux with IR LEDs On (Night)
Angle Of View	H: 51.2° (Wide) to 5.58° (Tele) V: 39.3° (Wide) to 4.27° (Tele)
Scanning System	2:1 Interlace
Effective Pixels (H x V)	752 x 582 (440K Pixels)
Video Format	PAL
Synchronisation	Internal / LL Selectable
Frequency	Horizontal: 15.625 KHz Vertical; 50.00Hz
Shutter Speed	ESC (x128~1/50~1/1.20,000), Manual (x128~1/50~120,000 Sec), Flickerless (1/120 Sec)
Video Output	1.0Vp-p / 75 Ohm
Day / Night	ON / AUTO Selectable
Gain Control	OFF / LOW / MIDDLE / HIGH
Back Light Compensation	OFF / LOW / MIDDLE / HIGH
White Balance	ATW / AWC / MANUAL / (1800°K~10500°K)
S/N Ratio	>50dB (AGC Off)
Sens-Up	OFF / AUTO x128
Camera Title	Selectable On/Off Maximum Of 15 Characters
O.S.D.	Yes Built-In
Motion Detection	ON / OFF (4 Programmable Zones)
DNR	OFF / LOW / MIDDLE / HIGH Selectable
Mirror	Built-In (Horizontal Image Inversion)
Privacy Function	ON / OFF (4 Programmable Zones)
IR Spectrum	850nm
Illumination Distance	Approximately 20 Meters*
IP Rating	IP66
Communication	RS485 Protocol: Pelco-D
Power Consumption	460mA. 800mA (With IR LEDs On)
Power Supply	DC 12V / AC 24V
Operating Conditions	Temperature: -10°C ~ +50°C, Humidity: 30 ~ 90% RH
Dimensions (W x H x D)	90.3 x 126.5 x 221.6 mm
Weight	900g
*Illumination distance quoted above is based on optimal conditions	

Features and specification are subject to change for further improvement without any notice.