Cost Analysis of a Camera-Based Robot Calibration System

Andrew A. Fratpietro [1] and M.J.D. Hayes [2]

1: Graduate Student, afratpie@mae.carleton.ca

2: Assistant Professor, jhayes@mae.carleton.ca

Carleton University, Department of Mechanical & Aerospace Engineering,
1125 Colonel By Drive, Ottawa, Ontario, K1S 5B6, Canada

September 26^{th}, 2003

Abstract

The purpose of this analysis is to evaluate the cost of purchasing and acquiring components, assembling and testing a camera-based system for calibrating robotic manipulators. This analysis includes the estimated cost of reassembling the previously designed baseline system, a list of alternative parts for this system and several possible improvements. Each suggested improvement is weighted against the baseline system in terms of benefit and cost. The report concludes with a suggested course of action for the development of this system.

Contents

1 Introduction

Robotic manipulators perform a variety of tasks in automated processes. Many of these tasks require a high degree of accuracy in the kinematic model that the robot must maintain over the course of its working life. This can be a difficult task for the robot controller when one considers the constant wear, fatigue, and stress to which the robot will be subjected. In order to maintain an accurate kinematic model, the robot needs to be calibrated on a near-continuous basis. A low-cost system that allows the measurement and correction of error in the kinematic model without disturbing the robot from its work-related tasks would be ideal for this situation.

The camera-based robotic calibration system uses images of a precision-ruled surface taken from a measurement head attached to the robot end-effecter to identify the error in the kinematic model of the robot. An appropriate correction to the model is then fed back into the robot controller, resulting in a higher degree of accuracy.

The baseline calibration system consists of several components: a precision ruled surface of which images are produced, a flat standard used for measuring the distance between the ruled surface and the camera, a CCD camera and lens used to produce images of the ruled surface, a framegrabber PC card used for capturing images produced by the camera, a light source used to illuminate the surface of the ruler, a distance sensor and associated data acquisition hardware used to measure distance between surface of the flat standard and camera, and a personal computer with the LabView or Simulink and Matlab software for reading and processing the information that is produced by the rest of the system.

2 Scope of the Cost Analysis

Three different approaches are used in the preparation and presentation of the cost analysis for this camera-based robotic calibration system.

2.1 Engineering Approach

The engineering approach assumes that the analyst has an extensive knowledge of the entire system and of the operation of each of its separate components. The extensive knowledge required for this type of approach can be gained through studying operations manuals, experimenting with similar components, and other general research pertaining to each component.

2.2 Analogy Approach

The analogy approach assumes that information regarding a system similar to the one being analysed is readily available and can be used as an analogue to the system under development. In the case of the camera-based robotic calibration system, a working prototype has been under development for several years and is used as a baseline for the current system under analysis.

2.3 Expert Opinion Approach

The expert opinion approach assumes that one or many individuals already have extensive knowledge of the system or system components. These individuals may have suggestions relating to their past experience regarding possible improvements to the system under development. Markus Leitner from Steinbichler worked on the previous iteration of the camera-based robot calibration system while at the Institute for Automation at the Mining University in Leoben, Austria, and is a knowledgable source of information for the current iteration.

2.4 Explaination of Currency

This analysis includes the costs associated with the purchasing of parts, delivery of parts, and integration and testing of the system. The costs of various parts are obtained from product catalogues, internet price lists, and through requests for quotes from the manufacturers or their distributors. An explanation of delivery and integration and testing costs is located in Appendix A of this report. It is possible that some assets for use in this system may be inherited from the Carleton University Department of Mechanical and Aerospace Engineering and other sources, but these assets remain in a state of uncertainty and will not be considered in this analysis. It can be noted that these assets may reduce the overall cost of the system.

All dollar values stated in this report are given in fiscal year 2003 constant Canadian dollars and as a result inflation is not considered.

3 Comparison of System Components

The camera-based robotic calibration system has several different components and each of these components should be evaluated separately. Each component evaluation consists of a brief description of the component in question, a list of constraints with their explanations, a description of the baseline design, a summary table filled with possible alternatives to the baseline, and a comparison of these possible alternatives. Each evaluation is followed by a recommendation and reason for this recommendation.

There is an overall payload constraint on the weight of the fully equipped measurement head imposed by the payload of the robot being used for validation of the system. This constraint is a 2 kg maximum mass. Therefore, the combined mass of all components mounted to and including the measurement head must not exceed 2 kg. It is also necessary that the all devices requiring an electronic cable attachment between the measurement head of the calibration system and a port external to the robot workspace use a cable configuration that does not interfere with the movement of the robot. For this purpose, all cables attaching to the measurment head must be at least 5 meters in lenth and will be fastened along the length of the robot from measurement head to robot base.

3.1 CCD-Camera

The CCD-camera is the transducer that converts an optical image of the ruled surface into a set of electrical signals that can be interpreted by a framegrabber PC card. This device is rigidly mounted to the measurement head and has its optical axis aligned in the negative z-direction of the robot tool-flange coordinate system. The CCD-camera must successfully integrate with an optical lens and communicate with a PC framegrabber card.

There are six parametric constraints placed on the selection of the CCD-Camera:
Colour -The use of colour is not required for the purpose of extracting metric information from digital images and can further complicate the procedure. Since cameras without colour regularly cost less than cameras producing coloured images, the selection of a CCD-Camera is restricted to black and white.
C-Mount Interface -There are several standard lens mount types that are common in industry. The most common for the purpose of attaching lenses to CCD-cameras in machine vision is the C-mount. An explanation of the C-mount is found in the appendix of this report. The selection of a CCD-camera is constrained to include a C-mount lens interface.
Analog -Analog cameras are typically cheaper and lighter then their digital counterparts. The selection of a CCD-camera is constrained to analog cameras.
Interlace scan -Interlace scan and progressive scan are two types of scanning that a CCD implements to produce images. A description of these scan-types can be found in the appendix of this report. The selection of a CCD-camera is constrained to interlace scan resulting in higher picture quality when compared to progressive scan at the same bandwidth.
Analog Interface -CCIR (Comité Consultatif International des Radiocommunications - International Radio Consultative Committee) video format regulates the transmission level and timing of a video signal. It is one of several well-documented video format standards and is used in this CCD-camera comparison out of convenience. This format implements a standard BNC cable for data transfer.
1/2 CCD Size -There are several common CCD sizes (1/3 inch, 1/2 inch, 2/3 inch). The 1/2 CCD size is selected as a constraint because it was selected in the baseline design and it is possibly the most common of the three common CCD sensor sizes.

The CCD-camera determined to be the baseline in this iteration of the camera-based robotic calibration system development is the Pulnix TM-6CN. Two features of this camera include manual high-speed shutter control and miniature size. Table 1 compares the Pulnix TM-6CN to two possible alternatives.

Alternative 1 is the Hitachi KP-M22-C. This camera offers a sizable weight reduction over the baseline design and also a reduction in cost when considering the camera alone. The power and video transfer cables for the KP-M22-C (Table 2) raise the total cost of this camera above that of the Pulnix TM6-CN. This camera is not recommended to be used in the current design iteration of the calibration system since it offers no significant advantage over the baseline design and a cost excess.

Alternative 2 is the Pulnix TM- 260. The advantages with this camera are a reduction in weight and an increase in frame-rate. The frame-rate of a camera is important to applications where the objects being imaged are moving relative to the camera axis. The camera-based robot calibration system uses a stop and shoot approach to imaging a ruled surface and so

Table 1: Comparison Table for CCD-Cameras

Specifications	Pulnix TM-260	Hitachi KP-M22-C	Pulnix TM6-CN
Digital /Analog	Analog	Analog	Analog
Colour	B+W	B+W	B+W
LensMount	C	C	C
Weight [*g*]	120	100	171
Resolution [*pixels*]	752x582	752x582	752x582
FrameRate [*fps*]	60	50	30
S/NRatio [*dB*]	50	56	50
PixelSize [*um*]	8.3x8.6	8.3x8.6	8.3x8.6
CCDSize [*inch*]	1/2	1/2	1/2
TVLines	560x420	560x575	560x420
ActiveArea [*mm*]		6.47x4.83	6.4x4.8
Sensitivity [*lux*]	0.5	0.3	0.5
Analog Interface	CCIR	CCIR	CCIR
Sync.	Internal External HD	Internal External HD	Internal
ScanType	Interlace	Interlace	Interlace
Cost [*CAD*]	1,125.33	822.61	872.11

Table 2: Comparison Table for CCD-Camera Accessories

Specifications	Pulnix TM-260	Hitachi KP-M22-C	Pulnix TM6-CN
Power Source [*CAD*]	109.32	185.61 (incl. trans)	109.32
Video Transmission [*CAD*]	12.95 (25 ft BNC)		12.95 (25 ft BNC)
TotalCost [*CAD*]	122.27	185.61	122.27

all relaive movement is removed and the frame-rate becomes less significant. The reduction in weight does not justify the increase in cost between the TM6-CN and the TM-260 and so the baseline Pulnix TM6-CN is recommended as the camera to be used in this system design iteration. This component will cost 1,059.10 dollars including the cost of delivery.

3.2 Camera Lens

The camera lens is required to magnify a clear image of a stainless steel ruled surface and project the image onto the surface of a CCD-camera imager. This device is required to be rigidly mounted to a CCD-camera and magnify images along the camera optical axis. The lens may also be required to rigidly mounted to the system measurement head depending on its mass.

There are three parametric constraints placed on the selection of the Lens:

C-Mount Interface -The lens interface is constrained to be type C-mount in order for the lens to be compatible with the CCD-camera.

Field Coverage -The field coverage of a lens is the area of the object in sensor view that the lens can focus onto a CCD sensor of a specific size. In the case of the camera-based robotic calibration system, at least three lines on the ruled surface must be observed on the CCD at any time (these three lines allow the movement of images of lines on the ruler to be easily tracked). Three lines on the ruler correspond to three millimetres horizontal distance. Therefore, the field coverage for a CCD sensor must have at least three millimetres in the horizontal direction. This field coverage corresponds to a magnification of roughly 2X.

F-Stop -The constraint on the F-stop (less than 0.1) insures that an appropriate amount of light will pass through the lens and that the image will be sufficiently bright enough for processing.

The lens determined to be the baseline for this iteration of system design is the Rodenstock MR2/O lens. This macro lens meets all specified constraints and additionally provides compact size. Table 3 offers a comparison between the Rodenstock MR2/O lens and 4 possible alternatives.

Alternative 1 is the Infinity InfiniStix 3x CCD-camera lens. This lens offers a significant reduction in cost, although several of the lens' characteristics have not yet been disclosed. It is expected that this lens will result in a large increase in image distortion and can not be recommended.

Alternative 2 is the Navtar Precise Eye 1.8x. This lens is comparable to the Rodenstock lens in most characteristics, although it's larger size and lower magnification allow it to appear less favorable than the baseline lens.

Alternative 3 is a telecentric lens from Sill Optics. This lens is also comparable to the Rodenstock lens in most characteristics. One disadvantage to this lens is its larger size and length compared to all other alternatives. This lens does have the advantage of being telecentric (removal of perspective distortion) while remaining extremly close in price to the baseline lens. It is for this reason that the Sill telecentric lens is the lens recommended for this iteration of the calibration system design. This component will cost 1,236.10 dollars including the cost of delivery.

Alternative 4 is the Lippolis MQM Series lens. This is also the most expensive lens in this analysis although it offers no significant advantage over the baseline Rodenstock lens.

3.3 Framegrabber

The framegrabber PC card is the device that receives the video signal from the CCD-camera in a specified format and then converts that signal into a digital image from which the PC can extract metric information. This device is inserted into one peripheral slot on the motherboard of the PC and the analog images are acquired through an interface with the CCD-camera.

There are six parametric constraints placed on the selection of the framegrabber PC card:
Analog -The framegrabber must be able to accept analog signals in order achieve compatibility with the CCD-camera.
Black/White -The framegrabber must be equipped to accept black and white images in order to achieve compatibility with the CCD-camera.
Analog Interface -The analog interface is constrained to be CCIR video format in order to achieve compatibility with the CCD-camera.
LabVIEW -The framegrabber is required to be accessible using the LabVIEW or Simulink software. This software is used to import images into the image-processing environment.
Interlace Scan -The framegrabber is required to be compatible with interlace scan CCD-cameras.
PCI Bus -The interface between the framegrabber and the PC is constrained to the PCI bus. This bus type allows the rapid transfer of high-resolution images from the framegrabber to the PC.

The framegrabber determined to be the baseline for this iteration of the system design is the NI PCI-1409. This framegrabber was implemented in the prototype design and meets all stated requirements. Two additional features include the availability of four separate inputs and 640 x 480 resolution. Table 4 compares the NI PCI-1409 to two possible alternatives.

Table 3: Comparison Table for Lens Component

Specifications	Rodenstock MR2/O	Infinity InfiniStix 3X	Navitar Precise Eye 1.8X	Sill Telecentric Lens	Lippolis MQM Series
Mount	C	C	C	C	C
Magn.	2x	2x	1.8x	2x	2x
Working Distance [*mm*]	75	68	92	87	75
$F - Stop$	0.076		0.071		0.076
Coverage 1/2"*CCD* [*mm*]	3.2x2.4	3.2	3.6x2.7	3.2x2.4	3.2x2.4
Distortion [*percent*]	0.2			0.2	0.2
Depthof Field [*mm*]	0.2				0.2
Diameter [*mm*]	16	15	26	30-40	16
Length [*mm*]	72.8	90	99.1	129	75
Cost [*CAD*]	1,117.13	707.10		1,119.78	1,356.66

Table 4: Comparison Table for Framegrabbers

Specifications	NI PCI-1407	Bitflow Raven 110	NI PCI-1409
Digital /Analog	Analog	Analog	Analog
Colour	B+W	B+W	B+W
BusType	PCI 32/33	PCI 32/33	PCI 32/33
Inputs	1	4	4
Resolution [*pixels*]	640x480	640x480	640x480
DataRate [*MHz*]	20	30	40
BitDepth	8	8	10
SDK [*um*]	LabVIEW	LabVIEW	LabVIEW
Memory Buffer [*MB*]			16
ClockType	Pixel Clock H/V Sync	Pixel Clock H/V Sync	Pixel Clock H/V Sync
Analog Interface	CCIR	CCIR	CCIR
ScanType	Interlace	Interlace	Interlace
Cost [*CAD*]	959.30	1,511.42	1,649.40

Alternative 1 is the Bitflow Raven 110. This framegrabber possesses most of the same characteristics as the NI PCI-1409 with a slight reduction in cost and the loss of the 16MB memory buffer. This design might be recommended if there was a requirement for 4 inputs on the framegrabber.

Alternative 2 is the NI PCI-1407. This framegrabber card has only one input port compared to the 4 input ports of the PCI-1409. This calibration sytem only requires the use of one input port and so the large cost reduction that the PCI-1407 offers result in the recommendation of the NI PCI-1407 for this iteration of the robot calibration system design. This component will cost 1,023.05 dollars including the cost of delivery.

3.4 Light Source

The light source is used to maintain a certain level of illumination on the ruled surface to be imaged. It remains rigidly mounted to the measurement head, powered by a separate cable, and directed towards the area on the ruled surface currently under investigation.

There are no parametric constraints placed on the selection of the light source, but several valuable points are considered:
1-The light source must provide a high level of contrast between the surface and the markings on the surface. This will allow greater accuracy in the extraction of metric information from these images.
2-The level of illumination should be reasonably constant in all images regardless of position and orientation of the measurement head. Constant levels of illumination will allow less complexity in the image processing algorithms.

The light source determined to be the baseline for this system is a red LED array. This device requires the additional design and manufacture of a mounting board and electronics. An estimate of the cost for implementing this design suggests approximately 100 dollars for parts (cable, LED array, resistors, voltage regulator, power source) and approximately 16 man-hours for design and construction of the device. All parts can be procured locally and so no delivery charges will be required.

One possible alternative to this design is the VarioFlash system that is available from The Imaging Source. This system consists of an LED array module (385.03 dollars), a five meter cable(67.62 dollars), and a power source(104.89 dollars). The cost of delivery of these parts is estimated to be 56.63 dollars and approximately 1 man-hour should be required to integrate the system. This results in a total cost of 614.16 dollars and one man-hour for implementing this design.

The baseline system appears to be the better option. It provides large cost savings over the alternative and will be recommended for the camera-based robot caliration system.

3.5 Distance Sensor and Data Acquisition Hardware

The distance sensor is a device that determines the distance along the optical axis of the camera between the camera and the ruled surface. This measurement is required in the calibration of the manipulator. The distance sensor remains rigidly mounted to the measurement head, powered and communicating through a single cable, measuring distance parallel to the

Table 5: Summary Table for Distance Sensor and Data Acquisition Baseline

Specifications	Component Cost [CAD]	Delivery Cost [CAD]	Cost [CAD]
Agilent 34401A Multimeter	1,543.73	97.84	1,641.60
MEL M5L/10	2,534.34	169.30	2,703.60
NI AT − GPIB/TNT (PCI)	915.00	64.19	979.19
TotalCost [*CAD*]			5,324.40

optical axis of the camera. The data acquisition hardware allows the information produced by this sensor to be read by the PC.

There are two constraints placed on the selection of the distance sensor and data acquisition hardware:
Resolution -The sensor is required to perform measurements to within a resolution of 5um. This measurement resolution is required for the high-precision calibration of the manipulator.
Interface Format -The electronic output of this sensor is required to remain compatible with some common PC data and physical format.

The baseline system for distance measurement implements a MEL M5/10 Laser Distance Sensor communicating with an Agilent 34401A Multimeter through a 25-pin D-connector cable. The multimeter is then interfaced through an IEEE 488 standard 24-pin connector and cable to an NI AT-GPIB/TNT (Plug and Play) ISA card that plugs into the ISA port in the personal computer. Most computers no longer implement the older ISA card interface and so the baseline is changed to an NI AT-GPIB/TNT (Plug and Play) PCI card. The estimated cost of implementing this solution as detailed in Table 5 is 5,324.40 dollars. This system offers rapid transfer of data with little loss in measurement data resolution over the transfer.

One possible alternative to the baseline distance sensor and data acquisition hardware is under investigation. This alternative involves the elimination of the Agilent 34401A Multimeter and the GPIB PC card. It may be possible to interface the MEL M5L/10 laser distance sensor directly to the PC serial port via the RS-232 transfer protocol. The MEL M5L/10 laser distance sensor can be packaged with an optional RS-232 interface to allow this connection. The only question that remains with respect to this interface is the loss in data measurement resolution. If this loss in resolution does not significantly effect the overall calibration error then this solution would offer significant cost savings from the baseline. This alternative is estimated to cost 2,703.60 dollars.

3.6 Measurement Head

The baseline design of the camera-based robot calibration system contains little information regarding the design of the measurement head. This device is required to rigidly and easily integrate with the robot end effector of most industrial-grade robotic manipulators. The measurement head is also required to provide mounting fixtures for the camera (possibly the lens), distance sensor, LED array, and a number of cables. The measurement head should be low weight and moderatly resistant to thermal deistortion. It is roughly estimated that such a device could be designed and built for approximately 200 dollars and 80 man-hours of labor, although further investigation will be performed.

3.7 Measurement Standards

The baseline design of the camera-based robot calibration uses two measurement standards to allow the calibration. The first standard is a stainless-steel flat straight edge with dimensions 1000x50x10 mm. This standard provides the laser distance sensor with a reference surface to measure displacement in the z-direction. This standard is fixed horizontally with respect to the robot base coordinate system. The second standard is a stainless steel ruled surface with dimensions 1000x20x20. The markings on this surface are the focus of the camera and are used to determine the displacement of the robot in the x- and y-directions. The ruled standard is fixed parallel to the flat standard in the horizontal plane with respect to the robot base coordinate system.

The alternative measurement standard is a precision ruled surface from Schlenker Enterprises Limited. This ruler can be purchased for a total cost of 578.72 dollars including delivery. There is little information given regarding the flatness of this device when compared to the certificate issued from PZA regarding the accuracy of their device. This accuracy will most certainly be required for the system under design. Also, a quote was not issued (although it was requested) regarding the unruled and flat measurement standard also required for this calibration system. The implementation of this device results in little cost savings when considering the cost of delivery of this one piece from Schleker Enterprises Ltd. and the flat standard from PZA. As a result, this device will not be recommended.

The baseline design will be recommended for the current iteration. The costs associated with this design are detailed in Table 6, but the total cost of obtaining these parts is 802.95 dollars.

Table 6: Estimated Cost of Flat and Ruled Measurement Standards

Component	Cost [CAD]
PZA $StraightEdge$ $w/certificate131011000$	134.50
PZA $PrecisionRule$ $w/certificate140001000$	550.82
$CostofPackaging$ $andDelivery$	117.63
$TotalCost$ $[CAD]$	802.95

3.8 Personal Computer

There was no baseline specification regarding the selection of a personal computer. As a requirement, this device must contain all input and output ports required by the other devices in the system. These ports include a PCI slot for a framgrabber card, a serial port for the distance sensor and a serial port for use with the robot controller. An optional port that may be considered in the future is an interface for operation the LED array. This connection is not required right at this point in time.

This PC that is recommended for this iteration of the calibration system design is the Digital Design Bronze Package available from CompuNation Computers Inc. in Ottawa. There no cost of delivery associated with this product since it can be procured locally. This PC includes periferals such as a monitor, keyboard and mouse, as well as a motherboard with 3 available PCI slots. The cost of this system is 1493.89 dollars.

4 Summary and Conclusions

A rough estimate of the total cost of this system is now available. Table 7 is a summary of the costs that will be incurred through the puchase and acquisition of each recommended component as well as an estimate of the man-hours required for integration and testing. The cost of this system is estimated to be 8,618.69 dollars and 426 hours of labour.

This cost estimate of 8,618.69 dollars represents the cost of the system recommended by the author of this document and is based on the reduction of system costs and the maintaining of system performance. A table summarizing the cost associated with using the baseline system can be found in Appendix B. It can be noted that the recommended system offers a savings of 3,260.44 dollars over the baseline system with the potential for no loss in performance.

Table 7: Summary Table of System Costs

Component	Labour Required [hours]	Cost of Component including delivery [CAD]
$Camera$ $PulnixTM6-CN$	80	1,059.10
$Lens$ $SillTelecentricLens$	40	1,236.10
$Framegrabber$ $NIPCI-1407$	40	1,023.05
$LEDArrayand$ $Electronics$	16	100.00
$MELM5L/10$ $w/SerialComm.$	80	2,703.60
$MeasurementHead$	80	200.00
$MeasurementStandards$	40	802.95
$PersonalComputer$	10	1,493.89
$TotalCost$	426	8,618.69

Appendix A

Cost of Delivery Estimate

The estimate of cost of delivery is calculated using the Federal Express rate of delivery calculator found on the internet at http://www.fedex.com/ratefinder/shipInfo. This calculator uses location and destination of the parcel, the mass of the parcel, an assumption regarding the shape of the parcel, and the estimated cost of the parcels contents to estimate the rate of cost of its delivery. This estimate includes most or all necessary tariffs associated with international delivery and courior pick-up of packages being delivered from a location within Canada or the United States. All rates assume the that the parcels are being delivered to the follow postal code:

K1S 5B6
Canada

This code refers to the location of Carleton University in Ottawa, Canada.

Table 8: Cost of Delivery Estimation

Product/Model	Distributor	Location Postal/Zip Code	Estimated Mass Camera+Accessory [kg]	Estimated Cargo Value [CAD]	Estimated Cost of Delivery via FedEx [CAD]
Camera *Hitachi* $KP-M22-C$	OPSCI	Colorado Spr.,CO USA 80918	0.100+0.3	818.59+185.61	64.76
Camera *Pulnix* $TM-6CN$	OPSCI	Colorado Spr.,CO USA 80918	0.171+0.3	872.11+122.27	64.76
Camera *Pulnix* $TM-260$	OPSCI	Colorado Spr.,CO USA 80918	0.120+0.3	1,125.33+122.27	65.86
Lens *Rodenstock* $MR2/O$	The Imaging Source	Charlotte,NC USA 28204	0.2	1,117.13	65.30
Lens *Infinity* *InfiniStix*	Infinity Photo-Optical Co.	Boulder,CO USA 80301-2458	0.2	707.10	63.65
Lens *Navitar* *PreciseEye*	Navitar	Rochester,NY USA 14623	0.2		
Lens *Sill* *Telecentric*	Eureca Messtechnik GmbH	Koln Germany 50769	0.2	1,119.78	116.32
Lens *Lippolis* *MQMSeries*	Lippolis Optical-Video Tech.	Rescaldina,MI Italy 20027	0.2	1,356.66	75.42
Framegrabber NI $PCI-1407$	OPSCI	Colorado Spr.,CO USA 80918	0.1	959.30	64.21
Framegrabber *Bitflow* $Raven110$	OPSCI	Colorado Spr.,CO USA 80918	0.1	1,511.42	66.42
Framegrabber NI $PCI-1409$	OPSCI	Colorado Spr.,CO USA 80918	0.1	1,649.40	66.97
VarioFlash *Cable* *PowerSupply*	The Imaging Source	Charlotte,NC USA 28204	0.08 0.1 0.1	385.03 67.62 104.89	56.63
Agilent *Multimeter* $34401A$	Tequipment.net	Hazlet,NJ USA 07730	3.6	1136.00	97.83
Sensor MEL $M5L/10laser$	Laseroptronix	Vallentuna Sweden 18362	0.1	2,534.34	169.30
$GPIB$ NI PCI	National Inst.	Austin,TX USA 78759-3504	0.1	915.00	64.19
Ruler $1000x20x20$ *Precision*	Schlenker Enterprises Ltd.	Hillside,IL USA 60162	4.0	479.14	99.58

Cost of Integration and Testing

The integration and testing phase of the camera-based robot calibration system development is the period of time during which all parts have been acquired and the only resource being used is man-hours of labor. The estimates of man-hours required are loosely based on a combination of the cost and the interface complexity of the parts being integrated. This basis assumes that more time should be spent with parts that cost more because these parts will be more difficult to replace. Also, parts that have complicated interfacing requirements (ie, require programming, mounting) will require more time to integrate. There are two categories of time alottment that are implemented. The first category is the work-day (8 man-hours). Parts that fall into this category require very little time to integrate (1 hour) and the remainder of a day to thoroughly test that the part is functioning exacly as expected. Some examples of work-day parts include cables and power sources. The second category is the work-week (40 man-hours). Parts that fall into this category require a larger integration time as a result of a more complex interface (ie, hardware/software design). Some examples of work-week parts include the framegrabber and distance sensor. Table 9 is a list of all components and an estimate of the time required for integration and testing.

Table 9: List of Labour Required for Integration and Testing of Specific Components

Component	Labour Required [man-hours]
Camera	80
Lens	40
Framegrabber	40
LEDArrayand Electronics	16
VarioFlashSystem	8
Sensor/Multimeter/ GPIBSystem	80
Sensorw/SerialComm.	80
MeasurementHead	80
MeasurementStandards	40
PersonalComputer	10

Appendix B

Cost of Delivery Estimate

The baseline camera-based robot calibration system was designed by Markus Leitner of Steinbichler while attending the Institute for Automation at the Mining University in Leoben, Austria. The costs associated with obtaining and assembling the components for this baseline design are summarized in the following table.

Table 10: Summary Table of System Costs for Baseline System

Component	Labour Required [hours]	Cost of Component including delivery [CAD]
$Camera$ $PulnixTM6-CN$	80	1,059.10
$Lens$ $RodenstockMR2/O$	40	1,182.43
$Framegrabber$ $NIPCI-1409$	40	1,716.37
$LEDArrayand$ $Electronics$	16	100.00
$DistanceSensor$ $MELM5L/10$	80	2,703.60
$Agilent34401A$ $Multimeter$	(included in MEL)	1,641.60
$NIAT-GPIB/TNT$ (PCI)	(included in MEL)	979.19
$MeasurementHead$	80	200.00
$MeasurementStandards$	40	802.95
$PersonalComputer$	10	1,493.89
$TotalCost$	426	11,879.13