jet INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2015, VOL. 61, NO. 2, PP. 165–170
Manuscript received June 8, 2015; revised June 2015. DOI: 10.1515/eletel-2015-0021

Optical Tracking System

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***Abstract*—The presented optical tracking system allows intuitive controlling and programming of industrial robots by demonstration. The system is engineered with low cost components. Using an active marker (IR-LEDs) in combination with a stereo vision configuration of the camera system and the selection of suitable algorithms for the process chain of the image processing a positioning accuracy in the range of millimeters has been achieved. The communication between the tracking system and the robot is realized by using the TCP/IP protocol via an Ethernet connection.**

***Keywords*—optical tracking, stereovision, industrial robots programming by demonstration**

I. Introduction

THERE are countless applications for optical position tracking systems. These systems can also be used to realize intuitive programming concepts for industrial robots. Using multiple cameras the spatial coordinates of an optical marker can be determined. The processing is done with three degrees of freedom and delivers coordinates in Cartesian form.

The path programming for industrial robots is a time consuming and cost-intensive process. An intuitive approach to control and programme robots can significantly simplify the set-up of automatized production sequences. Especially when small lot sizes are produced it becomes crucial to keep the resulting overhead costs low. The focus of current investigations concerning intuitive methods for path-programming is on processes where the mechanical system of the robot is manipulated directly by the user. The INTEACH concept for intuitive path-programming developed at the “Fraunhofer Institut für Produktionstechnik und Automatisierung“ in Stuttgart can be named representatively for such a strategy. This method uses a force-torque sensor system to generate the program for the robot [1]. Fig. 1 shows the applied process of leading the robot tool manually.

Using a position tracking system the offline programming of the robot becomes possible, since there is no robot for the programming process needed. The programming of following processes of production can be applied while the robot is executing previous manufacturing orders.

II. Objectives

The investigated research question focuses on methods determining the spatial position of defined optical markers using different camera setups. The measuring data is analysed and processed to realize robot-control by demonstration.

A suitable architecture for a position tracking system is presented. Further investigations concerning the signal processing chain, the camera system and the image sensors, the applied image processing (algorithms) as well as the communication between the robot control unit and the tracking system. Furthermore the system should be realized with low cost components.

Before the start of the position capturing process the system has to be calibrated. Therefore different methods of camera calibration have to be examined.

III. Methods

Based on the results of examinations a position tracking system is realised to generate spatial coordinates to control an industrial robot. The hardware concept uses a stereo vision camera set-up, a hand-operated control unit with an attached marker and a processing unit for data processing.

The process chain consists of the process stages of segmentation, the determination of the image coordinates and the calculation of the spatial coordinates. Using optical filters a suitable configuration of the cameras and the optical marker is found. Furthermore methods for camera and system calibration are defined. Paraxial and convergent configurations are compared and the achievable measuring accuracy is determined in a defined work space.

Fig. 1. Programming by demonstration [2]

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Special attention is given to the determination of suitable algorithms for calculating the spatial coordinates and for the calibration of the system taking into account optical distortions of the lens system. To track the path of motion, similar to the "Teach-in Process" lists of data points are recorded. Because the desired resolution at high trajectory velocities needs a powerful data processing unit, implementations using an embedded board and a standard personal computer are compared to examine the system limits for implementation. The communication between the tracking system and the robot is based on a client-server architecture. The data exchange is done via an Ethernet connection using the TCP/IP protocol.

IV. RESULTS

The realisation of the optical tracking system was based on the schematic system configuration shown in Fig. 2.

The communication between the cameras and the processing unit was realized using USB 2.0 connections. The desired path of motion is shown by operating the control unit by hand. The processing unit analyses the images delivered by the cameras and calculates the spatial coordinates of the marker.

A. *Signal Processing*

To calculate the position vector describing the spatial position of the marker, independently from the chosen method, three steps of analysing the images have to be executed. In a first step the object that is looked for has to be identified in the images. After the segmentation the image coordinates or the borders of the object in the image have to be found. In the next step the calculated data can be used to determine the spatial position of the marker. The described procedure that has to be applied is shown schematically in Fig. 3

A. *Segmentation and Image Coordinates*

The best results in the segmentation process were achieved with a configuration using an active IR-marker in combination with a lens system with an optical band-pass filter. With the applied filter the system reacts only in a narrow frequency band with the desired sensitivity.

Disturbances caused by environmental light sources can be largely suppressed this way. One disadvantage of this configuration is that the camera has to be modified in a way that it becomes possible to remove the band-pass filter during the calibration process. The geometric projection properties of the optical system are not changed by attaching or removing the filter.

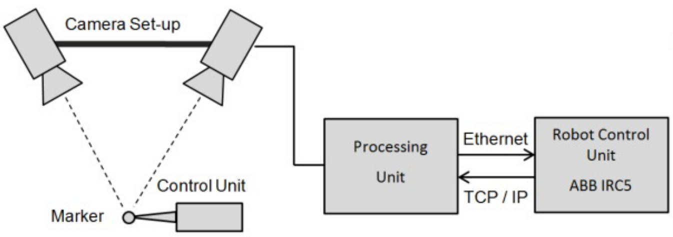

Fig. 2. System configuration.

Fig. 3. Image processing process chain

Fig. 4 shows the filter characteristics of the used optical filters as well as the emission characteristics of the marker. The image coordinates are determined in the next processing step using image moments.

Fig. 5 shows the realisation of the control unit with the attached active optical marker (a) as well as the camera enclosure (b) with the removable band-pass filter system that has been additively manufactured using a selective laser sintering process. The cylinder in the right section of the picture is a laser pointer that is integrated in the enclosure. After placing the camera at the desired position the projected point of the laser can be marked. Additionally the position of the tripod on floor has also to be marked. This way the configuration of the camera system can be easily reproduced at a later point.

B. *Calibration*

The process of calibration provides the system and camera parameters that are necessary for the calculation of the spatial coordinates. To achieve usable results by determining the position, distortion effects of the optical lens system have to be

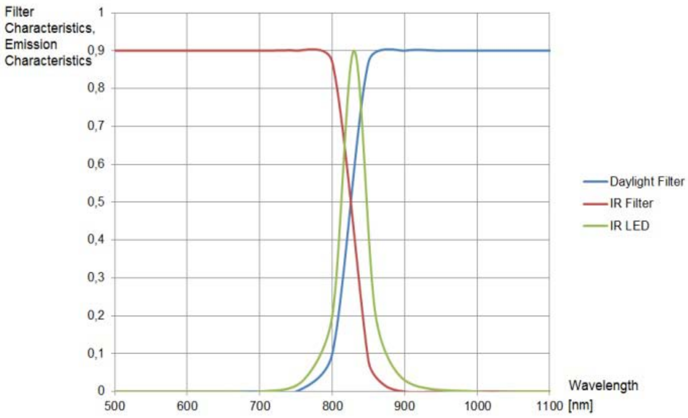

Fig. 4. Filter Characteristics, IR-LED Emission Characteristics - (red) IR-filter (blue) daylight filter and (green) emission characteristics IR-marker

(a) (b)

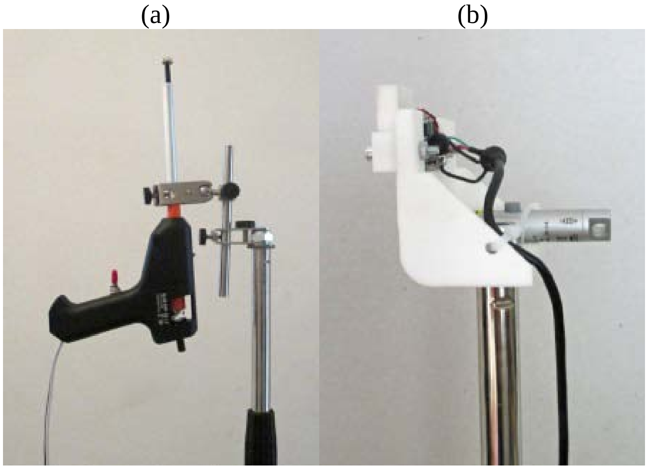

Fig. 5. Controlling unit and camera - (a) controlling unit with IR-marker and (b) additively manufactured camera enclosure with removable optical band-pass system

taken into account when performing the calibration for the individual cameras. Additionally the whole system has to be calibrated to identify the relative spatial positions of the cameras. A stereo calibration algorithm delivered by the image processing library OpenCV when used for convergent camera set-ups, delivers results that are only usable up to a very limited extend.

Especially the results of rectification (Fig. 6) based on Bouquet's algorithm when applied to convergent set-ups, are of limited usability. For the calibration of the individual cameras as well as for the calibration of the whole system a checkerboard pattern is used (Fig. 7).

C. Determining the Spatial Coordinates

An implemented algorithm for calculating the spatial position using the disparity matrix, when applied on approximately axially parallel camera set-ups, delivers satisfactory results.

Using the same algorithm for convergent, approximately right angled set-ups the calculated data do not meet the requirements.

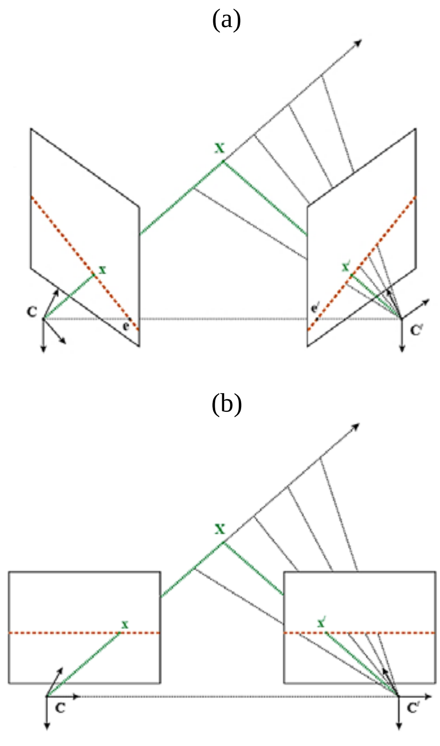

Fig. 6. Rectification process [8] – (a) before rectification, rectified images with aligned epipolar lines

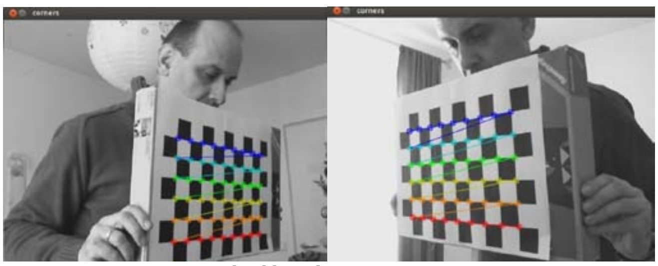

Fig. 7. Checkerboard pattern stereo vision

The use of the algorithm for configurations where the optical axes of the cameras cross at obtuse angles is therefore not suitable for the intended application.

Fig. 8 shows the geometric model used for the finally implemented algorithm for determining the spatial position. The cameras are used in a convergent set-up in this special case in an orthogonal configuration. The developed algorithm also delivers correct results for the general case of a stereo vision set-up. The necessary processing steps are listed in the performed processing order following as bullet points. Steps that have to be carried out once are:

- Calibration of the individual cameras (individual camera calibration)
- Determining the rotation and the translation vector between the cameras (stereo calibration)

Processing steps that have to be carried out cyclically are:

- Removing the distortions caused by the lens system from the captured images using the data from the individual camera calibration
- transforming the projection beam of the right camera into the coordinate system of the left camera
- Determining the intersection point of the images of the projection beams in the top view (determining the x- and the z- coordinates)
- Determination of the y-coordinate

When performing the implemented algorithm to determine the spatial coordinates only usable data delivered from the stereo calibration process is used. These are the rotation between the cameras and the displacement vector.

P_R describes the spatial position of the image of the marker in the right camera in relation to the coordinate system of the right camera (2).

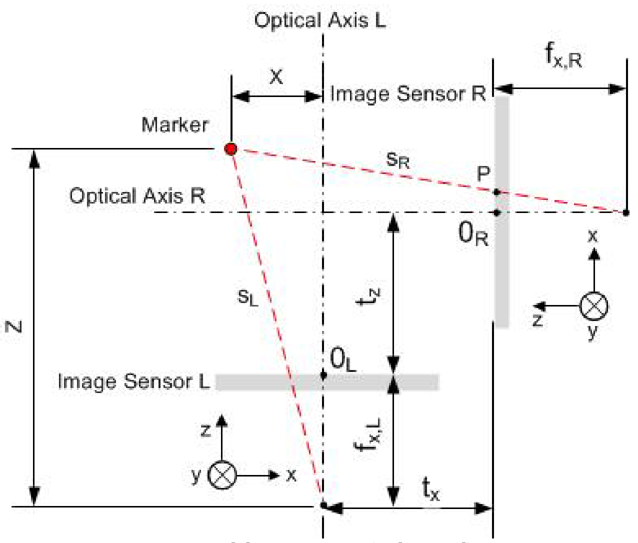

Fig. 8. Geometric Model: Convergent (orthogonal) stereo vision configuration - top view

$$P_R = \begin{bmatrix} (u_R - c_{x,R}) \cdot pix_{u,R} \\ (v_R - c_{y,R}) \cdot pix_{v,R} \\ 0 \end{bmatrix} \qquad (2)$$

u_R	Image coordinate, right camera
v_R	Image coordinate, right camera
$c_{x,R}$	Principal point x-coordinate, right camera
$c_{y,R}$	Principal point y-coordinate, right camera
$pix_{u,R}$	Pixel dimension in millimeters, right camera
$pix_{v,R}$	Pixel dimension in millimeters, right camera

s_R describes the direction vector of the projection beam of the right camera (3).

$$s_R = \begin{bmatrix} u_R - c_{x,R} \\ v_R - c_{y,R} \\ f_{x,R} \end{bmatrix} \qquad (3)$$

$f_{x,R}$	Focal length in pixel, right camera

In the next step the projection beam of the right camera has to be transformed into the coordinate system of left camera. P_L describes the spatial position of the point P_R in relation to the coordinate system of the left camera (4).

$$P_L = \boldsymbol{R} \cdot P_R + t$$
$$s_R' = \boldsymbol{R} \cdot s_R \qquad (4)$$

$\boldsymbol{R}$	Matrix describing the rotation between the cameras
t	Displacement vector, cameras
s_R'	Direction vector transformed projection beam

The following straight line equations (5) describe the projection beams.

$$z = \frac{f_{x,L}}{u_L - c_{x,L}} \cdot x - f_{x,L} \cdot pix_{u,L}$$
$$z = P_{L,z} + \frac{s_{R,z}'}{s_{R,x}'} \cdot x - \frac{s_{R,z}'}{s_{R,x}'} \cdot P_{L,x} \qquad (5)$$

x, z	Spatial coordinates of the marker
$f_{x,L}$	Focal length in pixel, left camera
u_L	Image coordinate, left camera
$c_{x,L}$	Principal point x-coordinate, left camera
$pix_{u,L}$	Pixel dimension in millimeters, left camera
$P_{L,x}$,	$P_{L,z}$ Transformed projection of the marker - coordinates
$s_{R,x}', s_{R,z}'$,	Transformed projection beam - coordinates

In the next step the spatial coordinates can be calculated according to formula (6).

$$x = \frac{P_{L,z} - \frac{s_{R,z}'}{s_{R,x}'} \cdot P_{L,x} + f_{x,L} \cdot pix_{u,L}}{\frac{f_{x,L}}{u_L - c_{x,L}} - \frac{s_{R,z}'}{s_{R,x}'}} \qquad (6)$$

Using this method a calculation of the coordinates at convergent set-ups with optical axis crossing at an angle of 90° becomes possible with satisfactory results.

D. Comparison of Camera Systems with Parallel Optical Axes and Convergent Stereovision Systems

An Analysis of the resulting properties of the measuring system shows that a stereo vision set-up with parallel optical axis and a small distance between the cameras represents a compact system but it shows a reduced ability to meet advanced measuring requirements. These limitations in measuring accuracy especially concern the coordinate axis parallel to the optical axis of the camera. Improvements can be made by the use of convergent camera set-ups with an appropriate distance between the cameras. Based on the results of this examinations the measuring system has to be realized in a way where configurations can be used where the optical axis of the cameras are crossing at an angle of 90°.

The measuring accuracy depends on the size of the desired work space and is indirectly proportional to the distance between the camera and the captured spatial point. The achievable measuring resolution can also be raised by an increase of the image sensor resolution.

The results of the comparison of paraxial and convergent stereo vision camera set-ups investigating the measuring accuracy are shown in Tab. I.

E. Communication

Conventional client-server architecture (Fig. 9) is used to realize the exchange of data between the system components. At the system start the TCP/IP connection between the tracking system (client) and the robot (server) has to be established.

TABLE I

ACHIEVABLE ACCURACY CONVERGENT, PARAXIAL SYSTEMS

	Convergent		Paraxial	
Distance spatial point [mm]	Distance point of convergence [mm}	Resolution x, y, z [mm]	Resolution x, y [mm]	Resolution z [mm]
659,84	500	0,97	0,97	13,04
989,76	750	1,45	1,45	29,63
1319,68	1000	1,94	1,94	53,21
1649,60	1250	2,42	2,42	83,99
1979,52	1500	2,91	2,91	122,18
2309,44	1750	3,39	3,39	168,03

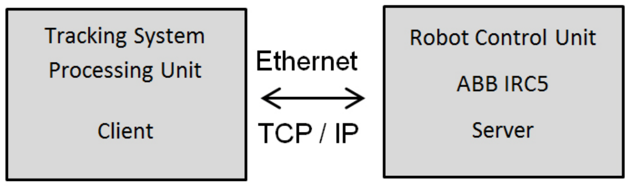

Fig. 9. Client server architecture

After the successful execution of the connection process the robot control unit indicates to the tracking system that the robot is ready to receive data. Current data describing the spatial position of the marker is than sent to the robot control unit. After the robot has executed the related operating command and has reached the desired spatial point, the robot control unit indicates to the tracking system that the control unit is waiting for the next data set.

F. *Platforms for Implementation*

In the process of implementation different parts of the code have been tested on an embedded platform as well as on a standard personal computer.

In first studies a simplified algorithm for calculating the spatial position has been implemented on an embedded platform. A Pandaboard ES (Fig. 10) was used for these studies. The Pandaboard ES is an evaluation board with an OMAP dual core ARM-A9 processor and a system clock rate of 1 GHz.

The system has 1 GB RAM. The used operating system was an Ubuntu 12.04 image which was especially optimized for Pandaboard's OMAP processor. For the implementation the image processing software library OpenCV has been used. Testing the described application the CPU-load of the embedded board reached the limits of the processing capacity.

Because of the provided higher processing power a standard personal computer with an Intel i7-4702MQ CPU with four cores and a system clock rate of 2.20GHz was used for this purpose, as the Pandaboard provided itself unsatisfactory.

The operation system that was installed on the personal computer was similarly an Ubuntu 12.04 image. The finally realized code can also be executed on the examined embedded platform.

But especially the process of stereo calibration causes extended processing times. Furthermore it should be noted that the final realization places higher demands on the processing power than the tested code on the embedded board.

V. CONCLUSION

A. *System Test*

The engineered system was subjected to function tests with the robot simulation software RobotStudio and it was also tested controlling an ABB robot. Fig. 10 shows the experimental set-up for the function test.

In the studies it has been shown that the tool-centre-point of the robot is following as required the specified controlling movements of the control unit.

Fig. 10. Experimental set-up function test ABB IRB 120

B. *Measuring Accuracy*

In further testing the actual measuring accuracy of the position tracking system has been examined. For that purpose the control unit has been attached to the robot arm with the help of an adaptive gripper. The cameras have been positioned in a way that the control unit could be placed in different defined spatial positions of the work space. After the calibration process the marker was moved through the captured region of the left camera.

The coordinates delivered from the robot as well as the coordinates measured by the tracking system have been recorded. Because the coordinate systems of the robot and the position tracking system were not perfectly aligned the magnitude of the displacement vectors were calculated on the basis of the recorded coordinates. In the following processing step the magnitudes describing the movements of the robot and measuring data of the tracking system were compared and an absolute error was determined. The results of this examination are shown in Fig. 11.

As a result of a verification of the measuring accuracy the expected values could be achieved.

VI. OUTLOOK

In following steps the measuring accuracy can be further increased by implementing algorithms for subpixel interpolation. In Fig. 12 the relationship between pixel and subpixel is shown schematically.

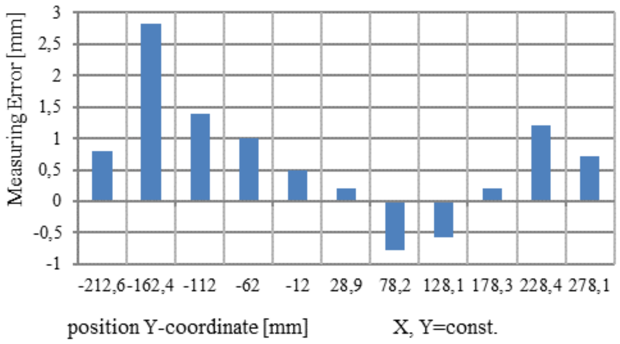

Fig. 11. Measuring error as a function of the marker position

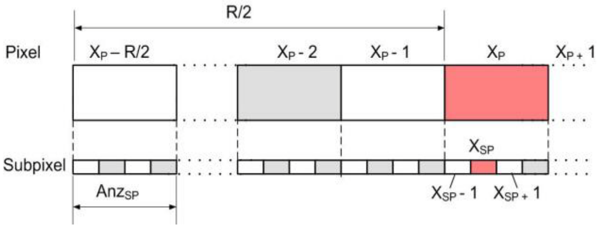

Fig. 12. Subpixelinterpolation

The measuring accuracy of optical systems can be raised up to a 50x improvement of the primary resolution using subpixel interpolation [7]. The calculation shown exemplarily for the x-coordinate can be made according to the following formula (7).

$$X_{int} = X_P - \frac{R}{2} - \frac{1}{2} + \frac{X_{SP}}{Anz_{SP}} - \frac{1}{2 \cdot Anz_{SP}} \qquad (7)$$

X_{int}	Interpolated spatial coordinate with increased resolution
X_P	Initial spatial coordinate value before interpolation
X_{SP}	Image coordinate in subpixel
ANZ_{SP}	Amount of subpixel pro pixel
R	Interpolated region

To provide measuring results of higher precision the process of calibration has to be optimized. In this context the suitable parameterizing for the calibration process has to be identified.

To achieve increased image frame rates further examinations are necessary. For this purpose it would be appropriate to investigate alternative ways of communication between the cameras and the processing unit. The analysed embedded board is restricted using only one camera via CSI (Camera Serial Interface). The use of boards with interfaces providing higher data rates for multiple cameras could be an option for improvements. For further optimisation several processing steps could be outsourced to the GPU (Graphics Processing Unit) of such a board.

In the meantime examinations of capturing multiple markers simultaneously have been made. As a result of these examinations a spatial position tracking with six degrees of freedom can be realized.

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