

## 3D measurement systems for robot manipulators

***Citation for published version (APA):***

van Beek, A. M. (1998). *3D measurement systems for robot manipulators*. (DCT rapporten; Vol. 1998.011). Technische Universiteit Eindhoven.

***Document status and date:***

Published: 01/01/1998

***Document Version:***

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

***Please check the document version of this publication:***

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

***General rights***

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

[www.tue.nl/taverne](http://www.tue.nl/taverne)

***Take down policy***

If you believe that this document breaches copyright please contact us at:

[openaccess@tue.nl](mailto:openaccess@tue.nl)

providing details and we will investigate your claim.

# **3D measurement systems for robot manipulators**

A.M. van Beek

WFW rapport 98.011

Coach: Bram de Jager

Faculty of Mechanical Engineering  
Eindhoven University of Technology (TUE)  
March 1998



# Summary

This report presents a survey of systems for independent measurement of the Cartesian 3D position of the end-effector of a robot manipulator. Several commercial systems are classified by their main technology. For each type one or more characteristic commercial products are presented to illustrate typical performance and limitations. The ultimate goal is to find a measurement system, or combination of measurement systems, suitable for the RRR-robot<sup>1</sup>.

It is found that a combination of both a high accuracy and a high update rate can be achieved only with optical systems. Optical (laser) tracking system can cover a large volume, but are extremely sensitive to disturbances of the line-of-sight(s). Vision based system with line scan cameras on the other hand, are limited to a smaller volume but are less sensitive to disturbance of the line-of-sight. Also, it is much simpler to integrate more viewpoints or cameras. With commercial CCD area cameras a comparable accuracy can be achieved, but the update rate is limited to 50 [Hz].

Acoustic systems are limited to an accuracy in the order of 1 [mm]. However, increasing the number of ultrasonic receivers is both simpler and cheaper than adding more cameras to a vision system. Ultrasonic receivers can provide time-of-flight data to a processor directly. The raw data from a digital camera requires more processing.

Inertial sensors can be used in conjunction with other technologies (e.g., optical or acoustic) to increase the overall update rate of the system and reduce the – short term – sensitivity to disturbances of the line-of-sight(s). The gain in update rate can be (partly) used for increasing the accuracy by averaging multiple measurements of the optical or acoustic system. Thus increasing the accuracy of the overall system. The price to pay however, is an increase in complexity (e.g., data processing) and cost.

Returning to the RRR-robot, especially the combination of high accuracy, high update rate and uninterrupted tracking, severely restricts the possible options. Only one technology remains: vision based ranging. Suitable commercial systems exist, but exceed the available budget by a factor 4 or more. Therefore, the remaining option to realize a 3D vision based measurement system is building a customized system. This can be either a CCD-area camera based system combined with inertial sensors, or a CCD-line camera based system. The latter is preferred mainly because with one single technology both accuracy and update rate requirements can be satisfied.

---

<sup>1</sup>The RRR-robot is a laboratory robot with three rotational degrees of freedom to test a variety of advanced nonlinear control strategies.



# Contents

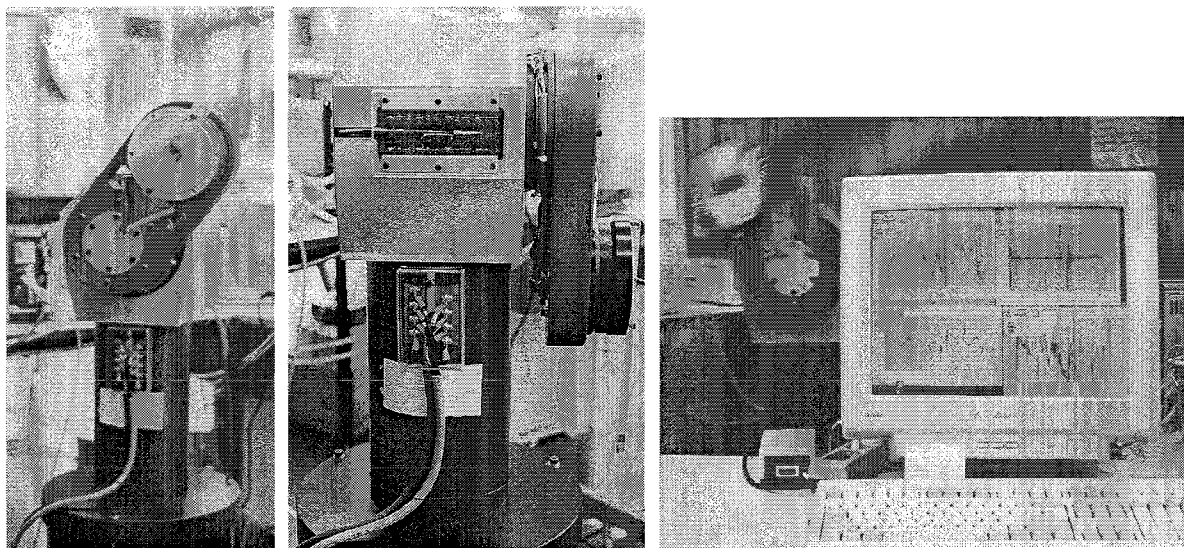
<b>Summary</b>	<b>iii</b>
<b>1 Introduction</b>	<b>1</b>
<b>2 3D measurement techniques</b>	<b>5</b>
2.1 Trilateration . . . . .	5
2.1.1 Time-of-flight measurements . . . . .	5
2.1.2 Phase-shift measurements . . . . .	6
2.2 Triangulation . . . . .	6
<b>3 3D measurement systems and sensors</b>	<b>9</b>
3.1 Mechanical . . . . .	9
3.1.1 Contact measurements . . . . .	9
3.1.2 Inertial measurements . . . . .	10
3.2 Electromagnetic . . . . .	12
3.3 Radio-Frequency (RF) . . . . .	13
3.3.1 GPS . . . . .	13
3.3.2 Harris Infogeometric System . . . . .	13
3.4 Optical . . . . .	13
3.4.1 Optical scanning systems . . . . .	13
3.4.2 Optical tracking systems . . . . .	14
3.4.3 Vision based ranging systems . . . . .	15
3.5 Acoustic . . . . .	19
3.5.1 Performance analysis . . . . .	20
3.5.2 Commercial systems . . . . .	21
<b>4 Conclusions</b>	<b>25</b>



# Chapter 1

## Introduction

**Objective** This report presents a survey of systems for independent measurement of the Cartesian 3D position of the end-effector of a robot manipulator. The purpose of this study is to get an overview of the various systems that are available on the market, and that might be applicable in case of the RRR-robot, see Fig. 1.1. This survey is certainly not exhaustive, but attempts to classify types of possible systems, and explore their performance and limitations. For each type one or more characteristic commercial systems are presented.



*Figure 1.1:* The RRR-robot: a laboratory robot with three rotational degrees of freedom to test a variety of advanced nonlinear control strategies. One of its main features is unconstrained rotation of each link [55, 56].

In industry, 3D measurement systems are used for kinematic calibration, i.e., to determine and compensate the deviations from the nominal construction parameters. The robot kinematic structure is often represented by DH (Denavit Hartenberg) parameters.



Using four parameters per joint, the position and orientation of each joint with respect to the previous joint is described: link length,  $a$ , distance offset along the rotation axis,  $d$ , the joint axis orientation angle,  $\alpha$ , and the joint rotation angle,  $q$ . With accurate (static) measurements, of the end-effector position

$$[x, y, z]_{\text{end-effector}} = \mathcal{F}(a_1 \dots a_n, d_1 \dots d_n, \alpha_1 \dots \alpha_n, q_1 \dots q_n)$$

with  $n$  joints/links in the Cartesian space, the deviation from the nominal parameters can be computed using a least-squares technique [49].

Another robotic application of 3D measurement systems is dynamic tracking of one or more points on an (intentional) elastic joint and/or link. This application is probably confined to experimental setups, e.g., Moudgal *et al* [38] use a vision system to determine the end position of a two-link planar flexible robot. The 3D measurements are used for performance evaluation, not for feedback.

**Specifications RRR-robot** Ideally, the 3D measurement system for the RRR-robot should be suitable for both high-speed dynamic tracking, and static kinematic calibration. However, in all Cartesian measurement system, a trade-off exists between accuracy and tracking velocity. Therefore, evaluation of the tracking performance – the main function of the RRR-robot – has priority.

The design requirements of the measurement system are determined by the specifications of the RRR-Robot as a whole, the implementation of the joint actuation system, the control system, the signal transfer system; and the design of a future flexible link and/or joint, see Table 1.1.

*Table 1.1:* Design specifications of a 3D measurement system for the RRR-robot. The available budget is NLG 50K.

---

1. *Accuracy*

The end-effector tracking accuracy is defined in Cartesian coordinates :

$$[x \pm \epsilon, y \pm \epsilon, z \pm \epsilon],$$

with  $\epsilon$  is 0.1 [mm] for static measurements, and 0.2 [mm] for reference inputs up to 5 [Hz], allowing for a gradual degradation down to 1 [mm] at 25 [Hz] inputs.

2. *Tracking volume*

The tracking volume is a sphere with a diameter of 1 [m]. In this volume of 0.52 [m<sup>3</sup>] the end-effector position should be measured without interruptions.

3. *Update rate*

To measure flexible modes up-to 500 [Hz] the update rate of the measurement system should be 1000 [Hz].

4. *Dynamic bounds*

Based on the nominal design and velocities the end-effector has a maximal linear tracking velocity of 6 [m/s] and a maximum acceleration of 50 [g].

5. *Interface*

The output of the measurement system, should be compatible with the chosen PC based control system.

---

Especially the combination of high accuracy, high update rate and uninterrupted tracking poses a difficult problem for most commercial systems and technologies. Therefore, the initial focus is on systems or technologies which could be used to measure the Cartesian position of robot manipulators in general. Possibly, the specifications can be met by combining two or more technologies or systems.

**Classification** Systems to determine the (Cartesian) position of a point in space can be found in a wide range of applications and on various scales. Large scale examples can be found in navigation techniques for ships, trucks or aircraft; the tracking of wildlife; and surveying. On a smaller scale applications can be particle tracking in fluids; motion analysis of athletes; tracking of markers inside animals; robot calibration; mobile robot positioning; and 3D input devices for computers.

Many of these applications have different and often conflicting requirements in terms of (1) position accuracy and resolution, (2) range or tracking volume, (3) update rate, (4) tracking velocity, and (5) the interface to the measurement system (e.g., allowable dimensions, mass of the sensor, or line-of-sight requirements).

Robot calibration for example, typically requires a high accuracy (0.01–1 [mm]) in a small tracking volume. The update rate is not important. Mobile robots on the other hand, operate in a much larger volume, and need faster measurements, but settle with a lower accuracy (10–100 [mm]).

Despite the differences in requirements, the used measuring techniques (e.g., triangulation or trilateration) and/or technologies (mechanical, electromagnetic, radio waves, optical or acoustic) are often similar, and can be used for multiple applications. Therefore in surveying possible techniques, measurement systems are classified by their basic technology, and not by the intended application.

**Outline of this report** This report is set up as follows. First in Chapter 2, a number of 3D measurement techniques are discussed. Then in Chapter 3, several 3D measurement technologies and commercial examples are presented. Finally in Chapter 4, all technologies are compared, and – based on Table 1.1 – a selection of possible systems to track the end-effector position of the RRR-robot is made.



## Chapter 2

# 3D measurement techniques

### 2.1 Trilateration

Measurement systems based on trilateration use distance measurements from a point with unknown position to three or more points with an exactly known position. In Fig. 2.1 this principle is graphically depicted for 3D measurements.

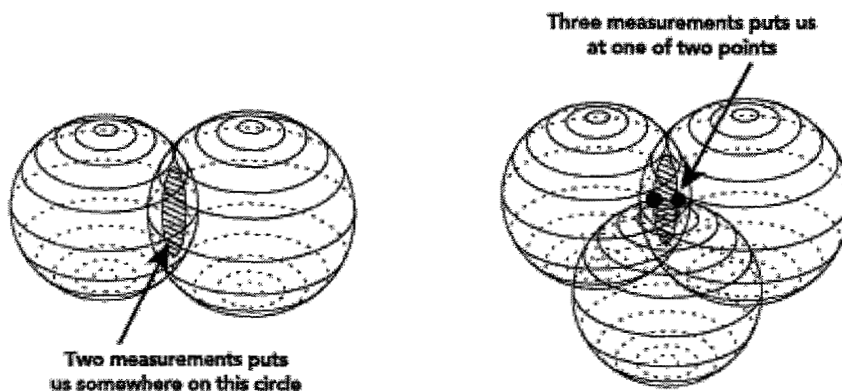


Figure 2.1: The principle of trilateration applied to GPS systems (Trimble Navigation Limited [36]).

Using three measurements results in two possible 3D point locations. In practice this is good enough, one of them can usually be eliminated based on its combination of position and velocity.

The distance can be measured using three different approaches; using mechanical aids (discussed in Section 3.1), determining the *time-of-flight* (TOF) of pulsed emissions between a transmitter-receiver pair, or by determining the *phase-shift* of a continuous wave transmission.

#### 2.1.1 Time-of-flight measurements

TOF range sensors typically use ultrasonic, RF, or optical emissions to measure the distance. The speed of the emission not only determines the possible update rate, but also imposes requirements on the timing accuracy.

Potential error sources for TOF systems [7] include the following:

- Variations in the propagation speed. Especially in acoustic systems where the speed of sound is significantly influenced by temperature or density (e.g., turbulence) changes, and to a lesser extent by humidity. See Section 3.5 for a more detailed discussion.
- Inaccuracies in the timing circuitry to measure the TOF. Sound in air travels at roughly 0.3 [m/ms], so to achieve an accuracy of 0.1 [mm] a timing accuracy of at least  $0.33 \cdot 10^3$  [ns] is needed. With the speed of light (0.3 [m/ns]) the required accuracy becomes  $0.33 \cdot 10^{-3}$  [ns].
- The occurrence of reflections. Resulting in multiple TOF measurements from one pulse emission.

### 2.1.2 Phase-shift measurements

Instead of short pulsed outputs used in TOF system, phase-shift measurements are based on continuous wave transmissions. In a transmitter-receiver configuration this requires an accurate synchronization (e.g., triggering and precise timing).

Using commercially available acoustic ranging electronic sensors [20], phase measurements can easily discriminate 0.075 [ $\mu$ s] intervals. However, they are limited to a maximum range of one wavelength, the so called ambiguity interval. So an acoustic system with a modulation frequency,  $f$ , of 40 [kHz] measures a distance with an ambiguity of a multiple of  $\lambda = \frac{c}{f} = 7.5$ [mm] ( $c=0.3$  [m/ms]).

For this reason phase-shift techniques are almost exclusively applied in optical ranging systems (with a much larger wavelength).

A promising concept in acoustic ranging is a combination of time-of-flight and phase measurements [20], Fig. 2.2. In this, not yet commercially available, system the phase information is used to improve the accuracy of a rough TOF measurement.

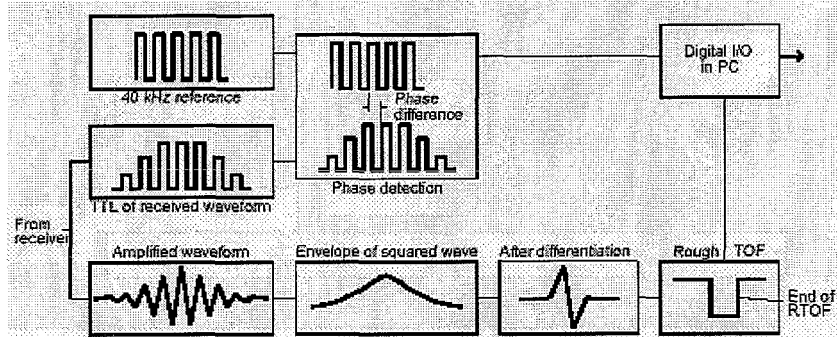


Figure 2.2: A combination of threshold adjusting and phase detection is employed to provide higher accuracy in time-of-arrival measurements in the Tulane University ultrasonic position-location system [20].

## 2.2 Triangulation

Measurement system based on triangulation use moving (scanning or tracking) transmitter and/or receiver combinations to measure multiple angles from one or more known reference

points. Combining angular and distance measurements (e.g., in optical laser tracking systems) is also considered triangulation.

Several triangulation algorithms exist [8]. In general, triangulation is sensitive to small angular errors when the observed angles are small, or when all reference points and the target are on or near a circle.

In contrast to trilateration the position accuracy is a direct function of the range. Therefore, the accuracy of such systems is often specified in [ $\mu\text{m}/\text{m}$ ], or parts per million [ppm]).



## Chapter 3

# 3D measurement systems and sensors

In the following sections several measurement systems and sensors will be discussed based on the following categories: mechanical, electromagnetic, radio-frequency, optical, and acoustic. The devices covered here are chosen to represent the achievable top performance of current systems in each category.

### 3.1 Mechanical

#### 3.1.1 Contact measurements

The simplest type of 3D measurement method uses auxiliary bodies to fix the manipulator in a known position (e.g., against a wall).

More advanced systems use cables or telescope arms to measure the distances and sometimes angles from known reference points to the end-effector. An example of a cable system is the *Calibration Plus* calibration system from Robot Simulation Ltd. [42, 35]. The end-effector position is measured by three cables extending from drums which are fixed to three corners of a roughly equilateral triangle somewhere in the workspace of the robot (see Fig. 3.1).

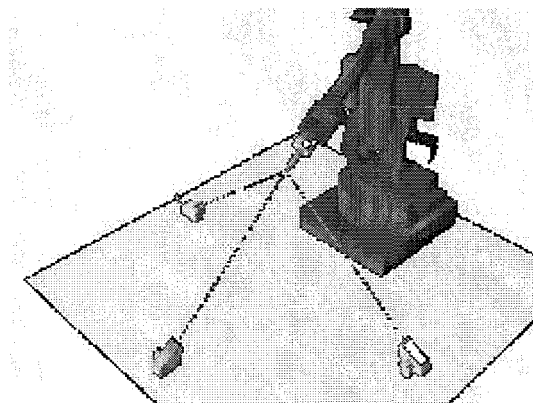


Figure 3.1: The *Calibration Plus* system from Robot Simulations Limited [35].



The (trilateration) system is self calibrating to an accuracy of 0.2 [mm]. The cable lengths determine the range of the system. The tracking velocity is constrained by the cable winding mechanism.

### 3.1.2 Inertial measurements

Inertial measurement sensors such as gyroscopes and accelerometers measure rotation rate, and acceleration, respectively. The measurements can be integrated to obtain the change in orientation (yaw, pitch and roll) and double-integrated to determine the changes in position ( $\Delta x, \Delta y$ , and  $\Delta z$ ). Inertial trackers have the advantage that they consist of self-contained, small, and light ( $< 0.5$  [kg]) units. No receiver/transmitter set-up is required. The possible update rate is limited only by sensor bandwidth. Another advantage of these sensors is a basically unlimited range, independent of the tracking accuracy.

However, integrating the data means that only relative orientation or position is measured; a known starting or reference point is required. Moreover, any constant error increases without bound after integration.

### Accelerometers

In an accelerometer, the deflection (force) of a proof mass is measured. Several techniques to measure or determine the deflection force can be distinguished, each with its own application range [57, 53]:

- Piezoelectric accelerometers use materials which develop electric charges when subject to time-varying forces. They do not respond to steady-state (DC) inputs such as the acceleration of gravity.
- Piezoresistive accelerometers use materials (e.g., micromachined silicon) which change in resistance when deflected by a (static or time-varying) force.
- Capacitive accelerometers use capacitive sensing elements (e.g., made of micromachined silicon) to measure the (static or time-varying) deflection of a proof mass. These sensors may be operated open-loop or closed-loop. In general, a closed-loop (or null-balanced/force-feedback/servo) accelerometer is more accurate – smaller nonlinearity and bias – and less sensitive to temperature influences.

In Table 3.1 the specifications of a number of representative commercial tri-axial accelerometers are summarized.

*Table 3.1:* Commercial tri-axial accelerometers. If the sensor is available in multiple g-ranges, the specifications for a second range are included between brackets.

System	Technology	Input range [g]	Frequency range [Hz]	Nonlin. [%]	Zero g Bias [g]	size [mm <sup>3</sup> ]	Remarks
AMP ACH-04-08-05 [2]	Piezoelectric	250	0.5-5000	0.1	0	11×10×1.8	7 wire connection, no DC output, mass $35 \cdot 10^{-3}$ [kg], price USD 200
Entran EGAXT3 [16]	Piezoresistive	10 (100)	0-240 (0-800)	1	1.87 (7.5)	-	
Silicon Designs 2430 [12]	Capacitive	10 (100)	0-400 (0-2000)	0.9	0.3 (3)	25×25×21	6 wire connection, low impedance, mass $30 \cdot 10^{-3}$ [kg], price USD 1100
Analog Devices ADXL05 [13]	Capacitive	4	0-100	0.2	0.2	35×25×19	5 wire connection
Wuntronc 34100A [59]	Capacitive closed-loop	50	0-2250	0.2	0.003	24×24×24	7 wire connection, large (temperature) stability

The most accurate DC sensor in this list, the Wuntronic 34100A, has a 0.2 % nonlinearity and a 0.003 [g] bias. In high performance closed-loop accelerometers the nonlinearity can be reduced down to 0.05 % [53]. So, after a measuring time of only 0.16 [s], and with a maximal acceleration of 10 [g] such a sensor may yield a position error  $\Delta s = \frac{1}{2} (0.002 \cdot 10 + 0.003) 9.81 t^2 = 0.1$  [mm].

### Gyroscopes

Although mechanical spinning mass gyroscopes are still used, the solid state “gyros” have become the dominant technology [46]. In a vibrating type gyroscope, a vibrating element is used to detect Coriolis acceleration effects orthogonal to the rotation.

Fiber-optic gyroscopes use the “Sagnac effect” [23]. The rotation rate is measured from the phase-shift between two light beams which travel in opposite directions through multi-turn coils of optical fiber wound around the rotation axis. In general, this type is more accurate, but also larger.

In Table 3.2, the specifications of a number of representative commercial gyroscopes are summarized. Because of the size of the individual components, commercial tri-axial gyroscopes units are not as common as tri-axial accelerometers.

Table 3.2: Commercial gyroscopes (with one rotation axis).

System	Technology	Input range deg/s	Frequency range [Hz]	Nonlin. [%]	Bias stab. [deg/s]	size [mm <sup>3</sup> ]	Remarks
Murata Gyrostar [39]	Vibrating piezoelectric	90	0-7	0.5	0.25	58×25×25	5 wire connection, mass 45 · 10 <sup>-3</sup> [kg], price USD 300
Systron Donner GyroChip II [15]	Vibrating piezoelectric	100	0-50	-	0.05	-	
KVH RD2100 [31]	Fiber optic	100	0-100	0.5	0.002	108×112×43	mass 0.34 [kg]
Litton μFORS-6 [37]	Fiber optic	1000	5-1000	0.2	0.00083	80×65×80	mass 0.150 [kg], price ± NLG 8K

Although the rotation rate is integrated once, the drift rate is considerable: after a measuring time of only 0.14 [s], and with a maximal rotation rate of 360 [deg/s], the Litton μFORS-6 may yield a position error  $\Delta \theta = (0.002 \cdot 360 + 0.00083) t = 0.1$  [deg].

### Inertial Measurement System (IMS)

In a complete 3D Inertial Measurement System, both translational and rotational sensors are needed to separate the kinematic from the gravitational acceleration. The idea is periodically to operate the system at zero velocity to identify the gravity acceleration vector. While moving, the orientation obtained from the gyros is used to compensate this constant acceleration [58, 53].

Thus, a complete 3D inertial sensor consists of three accelerometers, mounted perpendicular to each other, combined with three gyroscopes [29]. To identify the 1 g gravity acceleration vector at rest, the accelerometers must be DC responsive, i.e., sense both steady-state and changing signals.

The quality of a 3D IMS is determined by the quality of its components. In Table 3.3 some specifications of two Inertial measurement systems are summarized.

*Table 3.3:* Inertial Measurement Systems with three perpendicular accelerometers and three gyros.

System	Technology	Input range	Frequency range [Hz]	Nonlin. [%]	Bias	Dimensions entire unit
Crossbow	-	200 [deg/s]	0-10	0.5	1 [deg/s]	85.7×82.6×76.2 [mm <sup>3</sup> ]
DMU 6-axis [11]	-	50 [g]	0-100	0.2	0.005 [g]	0.475 [kg]
Systron Donner	vibrating quartz	500 [deg/s]	-	-	-	91.4×77.5×77.5 [mm <sup>3</sup> ]
MotionPak [15]	closed-loop	10 [g]	-	-	-	- [kg]

## Conclusion

Because the errors of both accelerometers and gyroscopes cause a significant error drift rate, inertial sensors alone are generally inadequate for periods of time that exceed a few seconds.

However, they can be used to provide accurate short-term information. Also, inertial sensors are often used in conjunction with other technologies (e.g., optical or acoustic) to provide periodical updates of the absolute position. Then the inertial measurements are used to increase the update rate of the entire system. Examples of such systems are discussed in Section 3.4 and 3.5.

## 3.2 Electromagnetic

A 3D electromagnetic measurement system is made up of a transmitter and a receiver, both consisting of three orthogonal coils. The variations in the received signal can be used to calculate the relative position and orientation of the transmitter/receiver with six degrees of freedom. Electromagnetic trackers are small, and accurate over a limited ( $< 2$  [m]) range.

However, in most robotic applications, the interference of ferrous metals located near the transmitter or receiver severely reduces the performance.

An example of a commercial system is the 3Space Fastrak from Polhemus [44] with a position accuracy of 0.76 [mm] RMS over a range of 760 [mm], and an update rate of 120 [Hz]. The target-receiver (23 x 28 x 15 [mm]) is completely passive, having no active voltage applied to it. The price of a complete system is approximately of NLG 6K.

### 3.3 Radio-Frequency (RF)

RF-based systems use active radio beacons and trilateration or triangulation techniques. Borenstein et al. [7, 8], performed an extensive study in mobile robot positioning. One of their main conclusions was that none of the currently existing RF-based trilateration systems work reliable indoors. Outdoors, GPS is promising to become the universal navigation solution. Since most robot manipulators are used indoors, RF-systems are discussed only briefly.

#### 3.3.1 GPS

The Global Positioning System (GPS) uses TOF measurements of RF-signals from satellites. With the exact distance from a ground receiver to three satellites (which momentary positions are broadcasted with the same RF-signals), the 3D position of the receiver can be calculated. Measurements from a fourth satellite are used to synchronize the receiver's internal clock.

To increase the accuracy, and counteract the effect of *selective availability* (deliberately introduced errors in timing and satellite position) differential GPS (DGPS) is used. These systems (see e.g., [36]) use a special receiver (USD 20K) at a precisely known position to determine an error correction for other DGPS-capable receivers (USD 2K) in the neighborhood (within 10 [km]).

During motion DGPS can achieve an accuracy within 1 [m]. When stationary for several minutes the accuracy can be increased to within 10 [mm].

#### 3.3.2 Harris Infogeometric System

The Harris Infogeometric [24] system is essentially a small scale version of the GPS system (tracking radius 500 [m]). Instead of satellites, fixed beacons are used for high speed (update rate  $> 1000$  [kHz]) trilateration between at least three beacons and a receiver. An accuracy of approximately 10-30 [cm] is claimed. However, in indoor applications, the existence of walls and other obstructions will reduce the accuracy due to reflections. The price of a basic system is approximately USD 30K.

### 3.4 Optical

There are three basic type of optical measurement systems. The more active systems involve some kind of mechanical moving mechanism which either scans for a target or tracks it. The third type are the passive, vision based ranging systems. All types require a line-of-sight to the target. However, differences arise in the capability to retrieve a previously obscured target. Especially optical tracking systems break down when the line-of-sight is lost.

#### 3.4.1 Optical scanning systems

An example of a 3D scanning system is the fixed beacon *Conac* system from MTI Research, Inc. The basic system consists of two fixed laser beacons (see Fig. 3.2) with a measurement range of 300 meters. These beacons, STROABs (Structured Opto-electronic Acquisition Beacon), scan the environment 50 times a second, resulting in an update rate of 46 [Hz]. Compared to other scanning systems [7] this is relatively fast.

A mobile Position Transponder detects the passing laser emissions and its location may be determined in 2 or 3 dimensions with an accuracy of  $\pm 1.3$  [mm]. Two precision encoders are used

to determine x- and y-position. Z-axis measurement is made by scanning a third laser from the second beacon. The geometry of this laser is such that it provides a signal that is unique to the z-position of the Position Transponder. The cost of a complete 3D system is about NLG 20K.

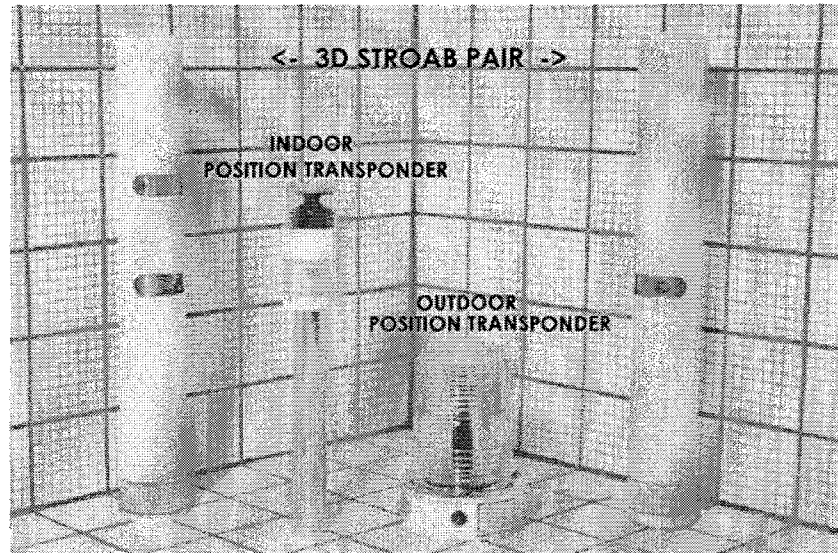


Figure 3.2: The Conac 3D tracking system from MTI Inc. [25].

### 3.4.2 Optical tracking systems

Optical tracking systems typically use one or more laser scanning heads aimed at a reflector by tilting and/or rotating mirrors. The reflector is designed to reflect the light beam parallel to its incident path but offset by a small distance if it does not hit the center of the target. The offset is detected by a photo sensitive detector, and fed back to the tracking controller to correct the offset, and return the laser beam to the target.

Optical tracking systems can achieve a high position accuracy (even in a large tracking volume), tracking velocity and update rate. However, if the line-of-sight is lost a timely re-initialization is required.

Various configurations are possible, based on triangulation or trilateration:

1. One scanning head with a laser interferometer (triangulation with two angles and one distance). This configuration is compact and requires only one line-of-sight. However, with interferometry only relative distances from a fixed reference can be measured. So when the line-of-sight is lost, the target must first return to the reference point.
2. Two scanning heads both measuring two angles to the target [51]. This triangulation based technique measures the absolute position of the target. Therefore after re-acquiring a previously obscured target, measuring can be resumed immediately.
3. Three scanning heads with interferometers. Because of the use of trilateration (no angles are measured) the accuracy is larger when compared to configuration 1 or 2. Obviously, now three lines-of-sight must be maintained.

### Components

**Laser interferometer** The basic idea behind laser interferometry is counting the number of illumination cycles of two interfering beams of (laser) light. The theoretical maximum resolution is half the wavelength, e.g.,  $0.25 \cdot 10^{-6}$  [m] for red light. The restricting factor, however, is the variation in the air's refracting index  $n_a$  due to changes in air pressure, temperature or humidity. Air pressure has the largest influence on the ranging accuracy [22, 48]: approximately  $\pm 10$  [ppm]<sup>1</sup> for a variation of  $\pm 0.33$  [mbar] ( $\pm 25$  [mm Hg]). The temperature effect is  $\pm 1$  [ppm] per degree Celsius. Some commercial systems provide continuous read-out corrections using pressure and/or temperature sensors; resulting in an overall ranging accuracy below  $\pm 2$  [ppm] for variations of  $\pm 5$  [K] and  $\pm 25$  [mm Hg].

**Angular measurements** Accurate translational displacement transducers (encoders and inductosyns<sup>2</sup>), using interpolation techniques, can achieve accuracies up to 1" ( $4.8 \cdot 10^{-6}$  [rad]) [14]. This translates in an accuracy of approximately  $\pm 5$  [ppm].

### Commercial systems

The Leica *LTD500* (see Fig. 3.3) is a system of the type one; it consists of a single measuring head with laser interferometer. The dynamic tracking accuracy (update rate 1 [kHz]) is  $\pm 40$  [ppm], i.e.,  $\pm 0.04$  [mm] per [m].

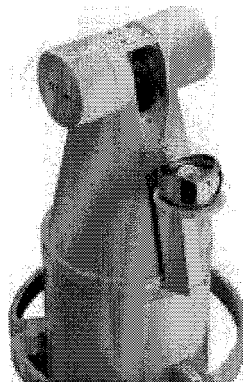


Figure 3.3: The *LTD500* 3D tracking system from Leica [33].

### 3.4.3 Vision based ranging systems

Vision based ranging systems use digital cameras to extract the 3D position of a certain point. In contrast to other vision applications they do not require high-level processing (e.g., feature extraction); the image data points themselves represent the geometric position of the target(s) [6]. These data points are acquired using (solid state) light sensitive elements connected in an array configuration.

<sup>1</sup>Parts per Million, i.e., accuracy in  $[\mu\text{m}]$  per [m] range.

<sup>2</sup>The inductosyn is a high-resolution incremental sensor based on the electromagnetic coupling between a fixed scale provided with an ac-excited conductor, and a similar but smaller sensing winding.

## Performance evaluation

**Optical limitations** The two factors that limit the image quality in an optical system are diffraction effects and lens aberrations [1, 52]. Diffraction effects result from the wave nature of light and the finite size of the lens [23, 41]. Using high quality optics with relatively low aberration levels, it is often the diffraction that places the upper limit on image quality [9].

The limiting resolution of a lens is specified as a spatial frequency, in a number of line pairs per millimeter [lppm]. For a general purpose lens the refraction limit is approximately 100 [lppm] for an aperture of  $f/8$  (a lens opening of  $1/8$  of the focal length). The pixel frequency in the focal plane should be significantly ( $2\text{--}10\times$ ) smaller [3].

If necessary, lens aberrations can be modeled and corrected. Elaborate aberration models including multiple distortion types exist, e.g., [50].

**CCD imaging limitations** Although several imaging architectures exist, the charge-coupled device (CCD) architecture dominates the market for solid-state area arrays [3]. This is because CCDs offer the greatest density of light sensitive elements and cost-effectiveness.

Several noise sources can reduce the gray-scale resolution (the brightness value at each pixel). At high read out rates and short-exposure conditions, *Readout noise* generated by the on-chip electronics is the dominant noise factor. As a rule of thumb, the RMS noise level or dynamic range represents a practical lower limit for the gray-scale resolution [9]. So a camera with a dynamic range of 1:20 [RMS] has only 20 effective gray levels, even with an eight-bit (256) display system.

**Area cameras** Area array, or matrix array cameras project 3D features (with coordinates  $[X, Y, Z]$ ) on a two-dimensional array of light sensitive elements (with  $[x, y]$ ). Because by projection the depth information is lost, at least 2 projections are needed to reconstruct 3D coordinates. Standard CCD area recording systems, compatible with broadcast television standards, have a relative measurement uncertainty between 1:5000 and 1:20000, i.e., on a range of 1 [m] an accuracy between 0.2 and 0.05 [mm] can be achieved. The update rate of these systems is rather low [21]. Using special purpose vision hardware, the processing and update rate can be achieved within a frame rate of 50 [Hz].

**Depth perception and resolution** In Fig. 3.4, an example of a dual camera configuration suitable for so called stereoscopic imaging is displayed [40, 5]. The optical axes are parallel and lie in the XZ-plane.

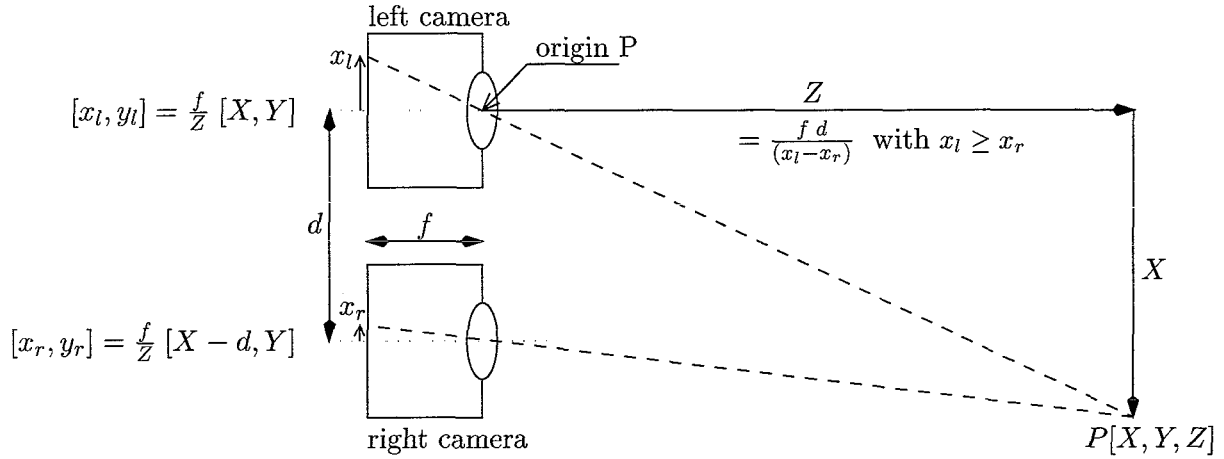


Figure 3.4: Stereoscopic imaging with *boresighted* cameras, i.e., parallel optical axes.  $f$  is the focal length

In a parallel configuration, the minimal range  $Z$  is considerable, i.e., the standoff distance (see Fig. 3.6) is large. For example with a focal length  $f$  of 100 [mm], an offset  $d$  of 1 [m], and a  $2048 \times 2048$  CCD with  $9 \times 9 \mu$  pixels, the standoff distance is

$$\min(Z) = \frac{f d}{\max(x_l - x_r)} = \frac{100 \cdot 10^{-3}}{2048 \times 9 \cdot 10^{-6}} = 5.4[\text{m}]$$

Therefore it may be necessary to converge the cameras in order to ensure that their fields of view overlap to include objects in the near field. Then the same techniques apply, but the range equations are more complex [9, 17]:

$$Z = \frac{f d}{2f \tan \theta - \Delta x} \quad (3.1)$$

where  $\theta$  is the convergence angle between each optical axis, and the normal on the camera separation length  $d$ . The difference  $\Delta x$  between  $x_l$  and  $x_r$  can now be positive or negative. Using a convergence angle  $\theta$  of 0.44 [rad] for the example system, (3.1) yields a depth of field (see Fig. 3.6) between 0.89 and 1.32 [m].

The *depth resolution* can be found by differentiating (3.1):

$$\frac{dZ}{d\Delta x} = \frac{Z^2}{f d} \quad (3.2)$$

So at the outer limit of the field of view of the example system, the resolution is

$$dZ = \frac{1.32^2}{100 \cdot 10^{-3} \times 1} \times 9 \cdot 10^{-6} = 0.16 [\text{mm}]$$

If the camera axes are not in the same plane, experiments are required to determine the image geometry experimentally (based on measurements of known positions) [60].

**Line array cameras** Line array cameras or line scan cameras consist of a linear array of light sensitive elements. Using cylindrical lenses (with a different focal length in each of the



two prime meridians [52]), 1-dimensional images of the object are projected perpendicular to three line arrays. Using similar depth perception techniques (e.g., 1 camera to determine the y-coordinate, and two cameras to determine the x- and z-coordinate), the 3D position of a light source can be determined.

Because there is only one line of pixels, the “frame rate” can be much larger than with area arrays. For example, a line camera with 2048 pixels, and a maximum pixel frequency of 3 [MHz] can achieve a frame rate of 1464 [Hz]. Another advantage over area arrays is the wider range of available resolutions.

**Resampling** The resolution of a vision system can be improved by resampling interpolation functions fitted on the original sampling points. This way the accuracy of the position sensor can be increased by a factor 2 to 5, independently of the optical limitations.

### Commercial systems

An example of a vision based system with CCD area cameras is the robot calibration system ICAROS from D\*ASS (“das Dienstleistungszentrum in die Dienstleistungsgesellschaft für Automatisierungs- und Signalverarbeitungssysteme”). This photogrammetrical system is composed of several digital cameras and an aiming target which is mounted to the robot end-effector and which consists of up to four infrared luminous marker balls. The system is available in various versions. The basic version (two cameras and PC-board, DEM 181.030,-) can achieve an accuracy of 0.03 [mm] in a tracking volume of 1 [m<sup>3</sup>]. For dynamic measurements (up to 1 [kHz]) an inertial sensor can be added [28].

Another CCD area camera system is the Triclops stereo vision system from Point Grey Research [45]. The system is used in mobile robotics and costs USD 3500. In Fig. 3.5, the quoted resolution is plotted v.s. the range (update rate 15 [Hz]). Assuming the cameras converge, and have  $16 \times 16 \mu$  pixels, (3.2) is used to calculate the resolution. To illustrate the influence of the focal length, the resolution is also calculated for a  $10 \times$  larger value of  $f$ .

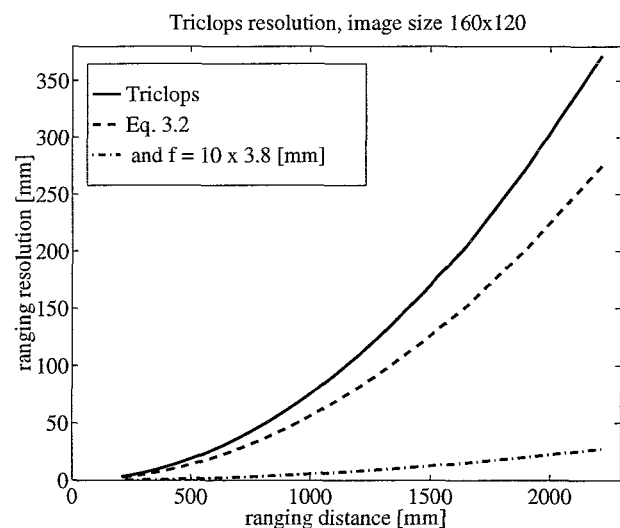
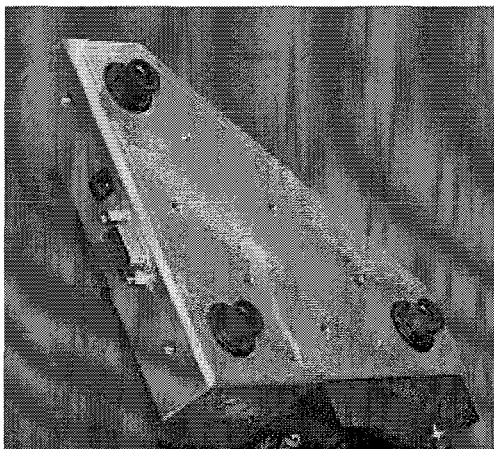
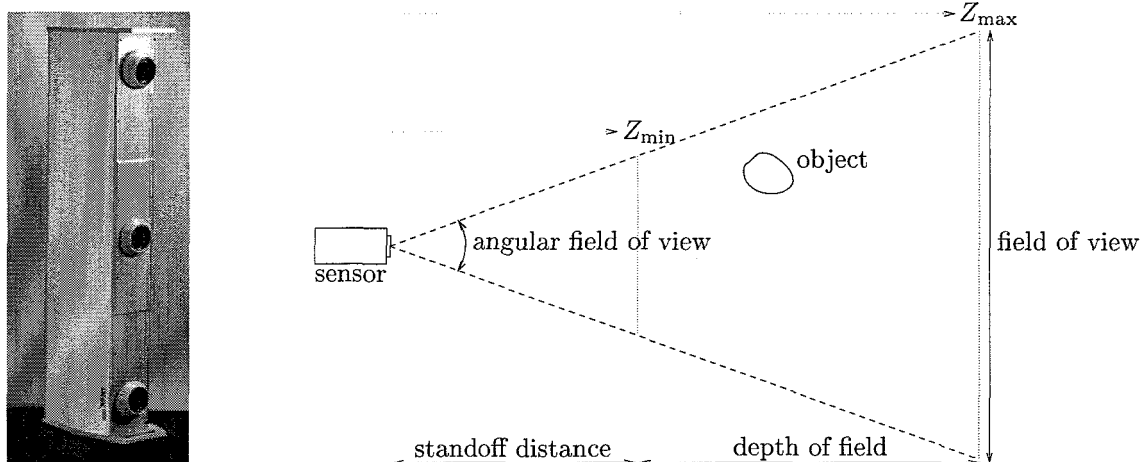


Figure 3.5: **Left:** the *Triclops* stereo vision system from Point Grey Research [45]. Three CCD area cameras are mounted in a  $0.14 \times 0.14$  [m] frame. **Right:** quoted and calculated ranging resolution v.s. range.

A commercial system using three line scan cameras is the Optotrak system from Northern Digital [26]. This system (see Fig. 3.6) can track up-to 256 infrared markers, with an update rate of

$$\frac{3500}{\# \text{ targets} + 1} \text{ [Hz]}$$

In a tracking volume of  $1.34 \times 1.28 \times 1.75 \text{ [m}^3\text{]}$ , an accuracy (RMS) between 0.1 and 0.3 [mm] can be achieved. The price of an Optotrak system with two viewpoints and real-time 3D capabilities is USD 120K (not including an additional PC).



*Figure 3.6: Left:* the Optotrak 3020 position sensor from Northern Digital [26]. Three line scan cameras are mounted in a 1.1 [m] long bar. *Right:* top view of a range imaging sensor with angular scan.

Schäfter & Kirchhoff [30] offer components for a similar customized system also using line array cameras. They quoted a system which can achieve an accuracy of  $< 0.3 \text{ [mm]}$  in a  $600 \times 600 \times 600 \text{ [mm}^2\text{]}$  measuring range ( $< 0.1 \text{ [mm]}$  in a sphere with a radius of 250 [mm]), and an update rate of 1000 [Hz]. The price of the components of a vision system with 6 line-scan cameras (2 viewpoints) is NLG 64907.50 (VAT excluded). An additional partial development (calibration, software) by Schäfter & Kirchhoff is possible at the expense of NLG 16230.62 extra (VAT excluded).

### 3.5 Acoustic

Ultrasonic measurement systems use trilateration techniques based on acoustic ranging. The systems under consideration measure the distance between one or more transmitters and multiple (3 for 3D) receivers.

Acoustic transmitters and receivers are readily available, cheap and reliable. However, there are some inherent limitations to the performance. Several researchers have examined the mechanisms that cause errors in ultrasonic ranging [20, 4]. Below the main performance limitations are summarized.

### 3.5.1 Performance analysis

**Line-of-sight** As with optical tracking a line-of-sight must be maintained between transmitter and receiver if errors are to be avoided. However, the moment the line-of-sight is restored, new 3D position updates become available.

The line-of-sight problem can be solved or reduced by adding more receivers. Since ultrasonic receivers pass their TOF data directly to the computer, not much additional processing is required. Note that ultrasonic sensors are also relatively cheap: approximately USD 50 [43, 10].

Figuerola and Mahajan [19, 18] propose a 3D ultrasonic system incorporating multiple receivers. With a minimum of 5 receivers in sight, the system is self-installing, and self-calibrating, i.e., the propagation speed of sound (see below) is eliminated from the ranging equations.

**Propagation speed** Changes in environmental conditions directly affect the speed of sound [54],

$$c_s = \sqrt{\gamma R T} \quad (3.3)$$

where,  $\gamma$  is the ratio of specific heats ( $c_p/c_v=1.4$  for air),  $R$  is the universal gas constant, and  $T$  is the temperature in [K]. Differentiating (3.3), the ranging sensitivity for temperature variations when measuring a distance  $s$  at a temperature  $T_0$ , can be determined, i.e.,

$$\left. \frac{ds}{dT} \right|_{T_0} = \frac{s}{c_s(T_0)} \left. \frac{dc_s}{dT} \right|_{T_0} \quad (3.4)$$

Thus a  $\pm 0.1$  [ $^{\circ}\text{C}$ ] variation in temperature results in an acoustic range variation of  $\pm 0.34$  [mm] when ranging a distance of 2 [m] at a temperature of 25 [ $^{\circ}\text{C}$ ].

Since, the top-range of commercially available thermometers is accurate to  $\pm 0.1$  [ $^{\circ}\text{C}$ ] [14], with direct temperature measurements only a very limited and costly performance improvement can be achieved. Also, if the air is not sufficiently calm and homogeneous, a grid of temperature points would be needed.

A better solution which also accounts for other influences (humidity and pressure), would be a continuous measurement of the speed of sound, either by measuring the TOF of a fixed calibration distance or by using additional ( $> 3$  for 3D) receivers.

**Update rate/latency** To simplify the processing (electronics), most commercial TOF acoustic system wait until a signal reaches the receiver before emitting the next signal. Then the maximum update rate is equal to the inverse of the maximum latency, and is limited by the speed of sound in air,  $c_s$ , and the largest transmitter-receiver distance,  $s_{\max}$ . In addition, some systems use an average of multiple ( $N_a$ ) distance measurements for one position update in order to minimize errors due to air turbulence. For these systems the theoretical maximum update rate for tracking  $N_t$  targets is given by:

$$f_{\max} = \frac{1}{\tau_d} = \frac{c_s}{s_{\max} N_t N_a} \quad (3.5)$$

where  $\tau_d$  is the maximum time delay between emission and reception.

Note that with separate receivers and transmitters, the pulse travels the distance  $s_{\max}$  from the target-transmitter to the receiver only once. This, in contrast to pulse-echo applications where an emitted pulse hits the target and bounces back.

**Transducer misalignment** Ultrasonic transmitters and receivers have finite sizes, resulting in a shorter TOF when both transducers' normals are misaligned (unavoidable in 3D applications). Laman, et al. [32] show that the acoustic distances must be corrected for accurate measurements of geometric distances in the order of  $\pm 0.1$  [mm]. Therefore, for each (accurate) application, misalignment plots must be experimentally generated.

**Timing accuracy** Present electronic technology can achieve a time resolution of at least 75 [ns], corresponding to an acoustic distance of 0.001 [in] (0.025 [mm]).

**Signal detection** To detect the arrival of a pulse, and distinguish it from echos, various techniques can be used. The most widely used method is thresholding, i.e., the arrival of a wave is acknowledged when the received signal exceeds a threshold level.

Experimental evaluation of this and other pulse detection techniques revealed detections errors resulting in range errors of  $\pm 0.010$  [in] ( $\pm 0.25$  [mm]). Combining thresholding with phase detection, as illustrated in Fig. 2.2, the accuracy can be increased by one order of magnitude [20].

### 3.5.2 Commercial systems

Commercial ultrasonic systems all use pulsed TOF measurements. Table 3.4 summarizes the specifications of three such systems.

The *FreeD* from Pegasus Technologies [34] is designed as 3D computer input device. The system can track one transmitter using 3 transceivers in an L-shaped frame, to be attached to the computer monitor. In correspondence with Pegasus Technologies an accuracy of  $\pm 0.2$  [mm] was claimed. Based on the previous discussion this seems unlikely, even if it is achieved at the cost of the update rate (which indeed is rather low).

The *V-scope* (see Fig. 3.7) marketed by Eshed Robotec has two special features: it uses three separate (not mounted on a frame) receivers which are self calibrating. In addition the receivers are equipped with ambient temperature sensors. Up to 8 transmitters can be tracked, but at the expense of the update rate.

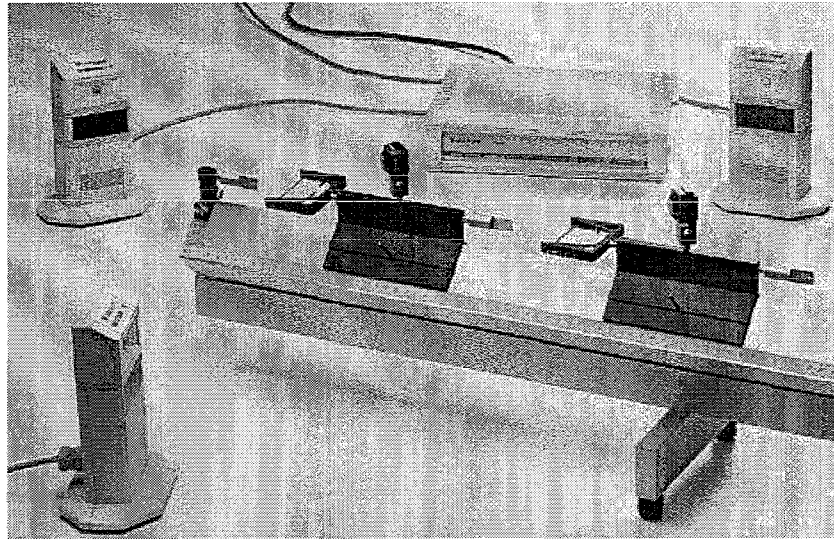


Figure 3.7: The *V-scope* measurement system from Eshed Robotec [47]. The three “towers” receive pulses from two targets or buttons mounted on the rail.

The *IS-600* from InterSense combines ultrasonic ranging with inertial measurements (3 angular rates of rotation and 3 linear accelerations) to determine the orientation of the transmitter and to increase the update rate. The time-of-flight is determined using three transceivers in an L-shaped frame, as can be seen in Fig. 3.8. The standard *IS-600* (USD 11,385) comes with one inertial sensor (expandable to 4) and three transponder beacons (expandable to 4).

Note that the ultrasonic system still determines the accuracy of the overall system. But now averaging techniques can be used to improve the accuracy of the ultrasonic measurements without consequences for the overall update rate.

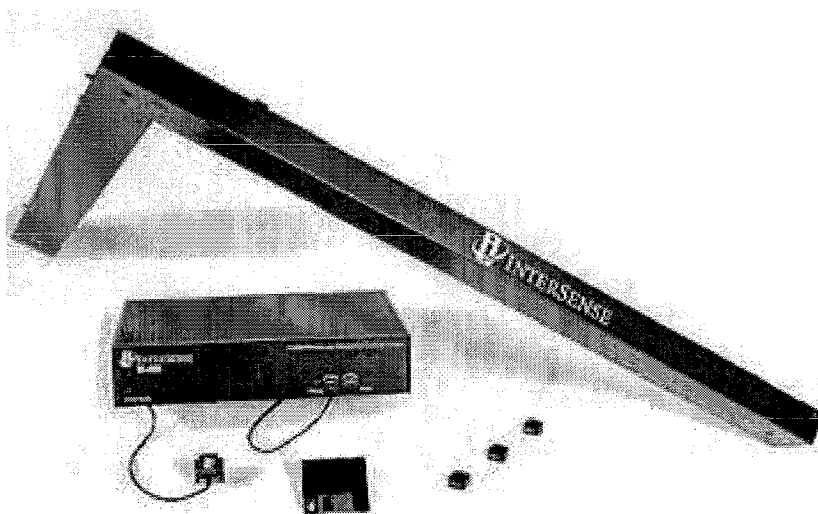


Figure 3.8: The *IS600* measurement system from InterSense [27]. The 3 receivers are at the end and corner point of the L-frame.

In the near future (probably March or April, 1998) an improved version will come available which uses trilateration based on more than 3 distance measurements. This IS-600 Pro has standard 4 receivers in a square frame but can be expanded with up to 16 receivers in 4 square frames to reduce or eliminate line-of-sight problems. With 8 receivers in two square frames the system will cost approx. USD 25,000. Note that this will be the only system with a standard capability of integrating more than 3 distance measurements.

*Table 3.4:* The specifications of commercial 3D ultrasonic measurement systems. Between brackets are the specification of a possible custom made improvement.

System	FreeD	V-scope	IS-600 (Pro)
accuracy [mm]	0.2	?	6.35 RMS
resolution [mm]	-	< 0.5	0.25
range [m]	0.9	5	-
update rate [Hz]	50	100	150
tracking velocity [m/s]	0.75 (1.5)	-	4.5
interface	RS-232	RS-232	RS-232
price [NLG $\times$ 1000]	0.2 (?)	8	26 (50)



## Chapter 4

# Conclusions

**Technologies** In Table 4.1 the specifications of several commercial systems for measuring the Cartesian end-effector of industrial manipulator are summarized.

A combination of both a high accuracy and a high update rate can be achieved only with optical systems. Optical (laser) tracking systems can cover a large volume, but are extremely sensitive to disturbances of the line-of-sight(s). Vision based system with line scan cameras on the other hand, are limited to a smaller volume but are less sensitive to disturbance of the line-of-sight. Also, it is much simpler to integrate more viewpoints or cameras. With commercial CCD area cameras a comparable accuracy can be achieved, but the update rate is limited to 50 [Hz].

Acoustic systems are limited to an accuracy in the order of 1 [mm]. However, increasing the number of ultrasonic receivers is both simpler and cheaper than adding more cameras to a vision system. Ultrasonic receivers can provide TOF data to a processor directly. The raw data from a digital camera requires more processing.

Inertial sensors can be used in conjunction with other technologies (e.g., optical or acoustic) to increase the overall update rate of the system and reduce the – short term – sensitivity to disturbances of the line-of-sight(s). The gain in update rate can be (partly) used for increasing the accuracy by averaging multiple measurements of the optical or acoustic system. Thus increasing the accuracy of the overall system. The price to pay however, is an increase in complexity (e.g., data processing) and cost.

Mechanical contact measurement systems offer a very simple and cost effective alternative for slow but accurate position measurements.

Electromagnetic measurement systems have specifications similar to those of acoustic systems. However, the presence of ferrous metals (electro motors) prohibits their use in robotic applications.

**RRR-robot** The design specifications of the 3D measurement system for the RRR-robot (see Table 1.1), especially the combination of high accuracy, high update rate and uninterrupted tracking, severely restrict the possible options.

Since the RRR-robot is designed to enable unconstrained joint rotation, it is inevitable that the line-of-sight from one single observer (camera or sensor) to the tip of the end-effector is lost during normal operation. Therefore, optical tracking systems and mechanical contact measurements can be ruled out.

Because acoustic system are not accurate enough, only one technology remains: vision based ranging. A combination of both a high accuracy and a high update rate can be achieved with



measurement systems based on line-array cameras. By combining multiple viewpoints also the line-of-sight problem can be (partly) solved.

In principle, also CCD Area cameras can be used, but only in combination with an inertial measurement system to improve the update rate. The inertial measurements also allow for a short ( $< 0.1$  [s]) loss of the line(s) of sight.

*Table 4.1:* The specifications of commercial 3D measurement systems. Between brackets are the specification of a possible custom made improvement. The lines-of-sight columns specifies the required number of lines-of-sight versus the total available viewpoints. So 3/8 means that three out of 8 lines-of-sight are necessary to extract a 3D position. All prices are in NLG (1 USD = 2.10 NLG, 1 DEM = 1.14 NLG, VAT **not** included).

System	Technology	Accuracy [mm]	Resolution [mm]	Range [m]	Update rate [Hz]	Tracking vel. [m/s]	# lines-of-sight: required/total	Price [NLG] × 1000
Calibration plus 3Space Fastrak <sup>1</sup>	Mechanical	0.2	-	$< 3$	unlimited	low	3/3	?
	Electro- magnetic	RMS	-	0.76	120	-	not required	6
DGPS <sup>2</sup>	RF	$< 10$	-	$< 10K$	$< 0.001$	-	3/4	44
Harris Infogeometric <sup>2</sup>	RF	300	-	500	$> 1000K$	-	3/?	60
Conac	Optical, scanning	1.3	-	2-300	46	-	2/2	20
LT500	Optical, tracking	0.04/[m]	0.01/[m]	25	1000	$> 4$	1/1, manual	?90
ICAROS <sup>3</sup>	Optical, vision	0.05	-	1	50 (1000)	-	2/2	200 (?)
Triclops	Optical, vision	-	$76 \times$ (range [m]) <sup>2</sup>	7	15	-	3/3	7.4
Optotrak	Optical, vision	0.1	-	2	$> 1000$	-	1/1	200
Schäfter <sup>4</sup>	Optical, vision	0.1	-	1	1500	-	1/2	65
FreeD	Acoustic	0.2	-	0.9	50	0.75 (1.5)	3/3	0.2 (?)
V-scope <sup>5</sup>	Acoustic	?	$< 0.5$	5	100	-	3/3	7
IS-600 (Pro) <sup>6</sup>	Acoustic	6.35 RMS	0.25	-	150	4.5	3/3 (3/8)	26 (5)

Remarks:

1. ferrous metals degrade the performance
2. not reliable indoors
3. modified version includes an inertial sensor
4. custom-made, components only (hardware and software)
5. automatic calibration and temperature compensation
6. inertial sensor ( $> 3$  receivers)

**Commercial systems** Northern Digital offers a complete ready-to-use measurement system, based on line-array cameras. This so-called Optotrak system also has the ability to combine multiple viewpoints without modifications. However it is expensive: NLG 200K, for a system with two viewpoints/sensors.

The ICAROS system (with CCD area cameras) is also outside the budget. Furthermore, the version with an added Inertial Measurement System is not yet commercially available.

So, no complete commercial system can satisfy all requirements, and is within the budget of NLG 50K.

**Customized vision system** The remaining option to realize a 3D vision based measurement system is building a customized system. This can be either a CCD-area camera based system combined with inertial sensors, or a CCD-line camera based system. The latter is preferred mainly because with one single technology both accuracy and update rate requirements can be satisfied.

Obviously, a customized system requires more effort than setting up an of-the-shelf system. A firm, such as Schäfter & Kirchhoff can supply components, experience and partial development. In general, a larger involvement of an outside party increases the cost, but it may also reduce the (financial) risk (depending on the particular agreement).

# Bibliography

- [1] Ansel Adams. *The camera*. The Ansel Adams photography series; Book 1. Little, Boston, 1995.
- [2] AMP. Tri-axial acclerometer ACH-04-08-01. <http://www.amp.com>, 1998.
- [3] G. W. Awcock and R. Thomas. *Applied image processing*. McGraw-Hill, 1996.
- [4] Enrique Barbieri and Fernando Figueroa. Experiments on identification and control of flexible structures using an ultrasonic ranging system. In *Proceedings of the IEEE Conference on Systems Engineering*, volume 116, pages 17–20, 1990.
- [5] Anthony Barrett. *Computer vision and image processing*. Applied information technology reports. Chapman and Hall, London, 1991.
- [6] Paul J. Besl. Active, optical range imaging sensors. *Machine vision and applications*, vol. 1:127–152, 1988.
- [7] J. Borenstein, H. R. Everett, and L. Feng. Where am I? Sensors and methods for mobile robot positioning. Technical report, The University of Michigan, 1996. Acrobat file available at <ftp://ftp.eecs.umich.edu/people/johannb>.
- [8] J. Borenstein, H. R. Everett, L. Feng, and D. Wehe. Mobile robot positioning: Sensors and techniques. *Journal of Robotic Systems*, vol. 14(no. 4):231–249, 1997.
- [9] Kenneth R. Castleman. *Digital image processing*. Prentice-Hal, Englewood Cliffs, 1996.
- [10] Massa Products Corp. Ultrasonic ranging systems. <http://www.massa.com>, 1998.
- [11] Crossbow. Inertial measurement system: DMU 6-axis. <http://www.xbow.com>, 1998.
- [12] Silicon Designs. Tri-axial acclerometer 2430. <http://www.halcyon.com/silicon/>, 1998.
- [13] Analog Devices. Tri-axial acclerometer ADXL05. <http://www.analog.com>, 1998.
- [14] E. O. Doebelin. *Measurement systems: Application and design*. McGraw-Hill, 1990.
- [15] Systron Donner. Gyroscope: GyroChip II. <http://www.systron.com>, 1998.
- [16] Entran. Tri-axial acclerometer EGAXT3. <http://www.entran.com>, 1998.
- [17] J. P. O. Evans, M. Robinson, S. X. Godber, and R.S. Petty. The development of 3-D (stereoscopic) imaging systems for security applications. In *IEEE Int. Carnahan conference on Security technology*, pages 505–511, 1995.

- [18] F. Figueroa and A. Mahajan. A robust navigation system for autonomous vehicles using ultrasonics. *Control Engineering Practice*, pages 49–59, 1990.
- [19] Fernando Figueroa and Ajay Mahajan. A robust method to determine the coordinates of a wave source for 3-D position sensing. *Journal of Dynamic Systems, Measurement, and Control*, vol. 116:505–511, 1994.
- [20] J. F. Figueroa and J. S. Lamancusa. A method for accurate detection of time arrival: Analysis and design of an ultrasonic ranging system. *J. Acoust. Soc. Am.*, vol. 91(no. 1): 486–494, 1992.
- [21] J. O. Gray and D. G. Caldwell. *Advanced Robotics & Intelligent Machines*. The Institution of Electrical Engineers, London, 1996.
- [22] Oliver S. Heavens and Robert W. Ditchburn. *Insight into optics*. Wiley, Chichester, 1991.
- [23] Eugene Hecht. *Optics*. Addison-Wesley, Amsterdam, 1998.
- [24] Harris Technologies Inc. Harris Infogeometric system. Clifton, Virginia, USA, phone: +001 703 2660904, 1998.
- [25] MTI Research Inc. Conac: Computerized Opto-electronic Navigation and Control. <http://www.mtir.com>, 1997.
- [26] Northern Digital Inc. Optotrak 3D position sensor. <http://www.ndigital.com>, 1998.
- [27] InterSense. IS-600 precision motion tracker. <http://www.isense.com>, 1997.
- [28] H. Janocha and B. Diewald. Icaros: Over-all-calibration of industrial robots. *Industrial Robot*, vol. 22(no. 3):15–20, 1995.
- [29] H. Janocha and D. Schmidt. Requirements for inertial sensor systems for measuring robot positions. *Robotica*, 8:145–150, 1990.
- [30] Schäfter & Kirchhoff. Optical components (line scan cameras). Celciusweg 15, 22761 Hamburg, phone: +49 40 8512562, fax: +49 40 8503137, 1998.
- [31] KVH. Gyroscope RD2100. <http://www.kvh.com>, 1998.
- [32] J. S. Lamancusa and J. F. Figueroa. Ranging errors caused by angular misalignment between ultrasonic transducer pairs. *J. Acoust. Soc. Am.*, vol. 87:1327–1335, 1990.
- [33] Leica. 3D laser tracker LTD500. <http://www.leica.com>, 1997.
- [34] Pegasus Technologies Limited. FreeD - The wireless 3D joystick. <http://www.pegatech.com>, 1997.
- [35] Robot Simulations Limited. Calibration Plus. <http://www.rosl.com>, 1997.
- [36] Trimble Navigation Limited. How GPS works. <http://www.trimble.com>, 1997.
- [37] Litton. products: Dynaserv sevos,  $\mu$ FORS-36 gyroscope, and various sliprings. <http://www.litton.com>, 1997. No online datasheet.

- [38] Vivek G. Moudgal, Kevin M. Passino, and Stephen Yurkovich. Rule-based control for a flexible-link robot. *IEEE Transactions on Control Systems Technology*, vol. 2(no. 4): 392–405, 1994.
- [39] Murata. Gyroscope Gyrostar. <http://www.murata.com>, 1998. No online datasheet.
- [40] Takanori Okosh. *Three-dimensional imaging techniques*. Academic Press, London, 1976.
- [41] Donald C. O'Shea. *Elements of modern optical design*. Wiley series in pure and applied optics. Wiley-Interscience, Chichester, 1985.
- [42] J. Owens. RoboTrak: Calibration on a shoestring. *Industrial Robot*, vol. 21(no. 6):10–13, 1994.
- [43] OEM Components group Polaroid Corp. Ultrasonic ranging modules. <http://www.polaroid-oem.com>, 1998.
- [44] Polhemus. 3Space Fastrak. <http://www.polhemus.com>, 1998.
- [45] Point Grey Research. Triclops stereo vision system. <http://www.ptgrey.com>, 1998.
- [46] M. Reunert and B. Yoshida. Fibre-optic gyroscopes: A new sensor for robotic and autonomous vehicles. *Sensor Review*, vol. 16(no. 1):32–34, 1997.
- [47] Eshed Robotec. V-scope 3D motion detection system. <http://www.eshed.com>, 1997.
- [48] P. H. J. Schellekens, K. Struik, and H. W. P. van der Schoot. *Werktuigkundige Meettechniek*. Technische Universiteit Eindhoven, Vakgroep Precision Engineering, Dictaat 4629, 1991.
- [49] Lorenzo Sciavicco and Bruno Siciliano. *Modeling and control of robot manipulators*. McGraw-Hill series in electrical engineering. McGraw-Hill, London, 1996.
- [50] Robert R. Shannon. *The art and science of optical design*. Cambridge University Press, 1997.
- [51] G. Simon. Optotrak - Cat's eyes and lasers. *Industrial Robot*, vol. 21(no. 6):18–21, 1994.
- [52] Warren J. Smith. *Practical optical system layout, and use of stock lenses*. McGraw-Hill optical and electro-optical engineering series. McGraw-Hill, New York, 1997.
- [53] D. H. Titterton and J. L. Weston. *Strapdown inertial navigation technology*. Peregrinus, London, 1997.
- [54] John D. Turner and A. J. Pretlove. *Acoustics for engineers*. MacMillan, London, 1991.
- [55] B. van Beek and B. de Jager. RRR-robot design: basic outlines, servo sizing, and control. In *Proceedings of the 1997 IEEE internat. Conf. on Control Applications (Hartford, CT)*, pages 36–41, NJ, 1997. IEEE, Piscataway.
- [56] Bert van Beek and Bram de Jager. An experimental facility for nonlinear robot control. Submitted for presentation at the IFAC Workshop on Motion Control, 1998.
- [57] C. Verplaetse. Inertial proprioceptive devices: Self-motion-sensing toys and tools. *IBM systems journal*, vol. 35(no. 3):649–650, 1996.

- [58] E. von Hinüber and H. Janocha. Inertial measurement system for calibration and control of robots. *Industrial Robot*, vol. 20(no. 2):20–27, 1993.
- [59] Wuntronic. Tri-axial acclerometer 34100A. <http://www.wuntronic.com>, 1998.
- [60] Y. Yakimovsky and R. Cunningham. A system for extracting three-dimensional measurements from a stereo pair of TV cameras. *Computer graphics and image processing*, vol. 7: 195–210, 1978.