Tooltracker
Pre-Study

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Abstract

This State of the art report investigates the possibility to create an indoor positioning system for an industrial environment with an accuracy of 10 mm. The research project is conducted as a joint project together with the external client Atlas Copco. The research method has been a deep-scan of current state of the art solutions and techniques for indoor positioning systems. They have been evaluated against the requirements set together with Atlas Copco. Furthermore, the evaluation included the authors' prior knowledge about the techniques and confidence in the techniques. The result shows that there are techniques possible to solve the requirements one by one. Although, there is no solution capable of meeting all of them. The next step of this project has two options; continue with the same requirements at a higher risk or alternate some of the requirements to decrease the risk of the project outcome. Finally, a family of four concepts have been developed.

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Abbreviations

AC	Alternating Current
AoA	Angle of arrival
DC	Direct Current
DOF	Degrees of Freedom
CoO	Cell of Origin
EPAM	Extended Phase Accordance Method
IMU	Inertial Measurement Unit
IR	Infra Red
LED	Light Emitting Diode
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NLOS	Non Line of Sight
LOS	Line of Sight
RF	Radio-frequency
RFID	Radio-frequency Identification
RMSE	Root Mean Square Error
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SLAM	Simultaneous Localisation and Mapping
SPL	Sound Pressure Level
TDoA	Time Difference of Arrival
ToF	Time of Flight
UWB	Ultra-wideband

1 Introduction

1.1 Background and Objective

The objective of this report is to give a pre-study to solve the problem of: *Localising a tool inside a manufacturing plant in order to make automatic settings to the tool depending on location.*

In the industry, the need for knowing how much to tighten a bolt is a part of quality assurance. Today these settings are done by hand for handheld tools, automatic settings would eliminate human error.

1.2 Requirements

Requirements are a vital part in a product design process. Requirements are a major guideline for defining the possible technologies, or what direction the state of the art research needs to be heading.

1.2.1 Functional Requirements

Accuracy:

- The system shall be able to measure the central position of the outgoing tap of the tool with accuracy of 10 mm when at a distance of 600 mm or closer to the target.
- The system shall be able to measure the central position of the outgoing tap of the tool with an accuracy of 500 mm inside a work space.

Output:

- The system shall update the position of the tool with a frequency of at least 10 Hz.
- The system shall output the position of the tool in the form of a Cartesian coordinate system in three-dimensional space (X, Y, Z) and the normal vector of the outgoing tap.
- The origin of the Cartesian coordinate system shall be defined as a fixed point in the work space.
- The systems position lag shall not be greater average human reaction time, estimated to 200 milliseconds.

1.2.2 Soft requirements

Accuracy: The system shall be able to measure the central position of the outgoing tap of the tool with an accuracy of 2000 mm when located in a global indoor positioning system.

Intrusiveness: The worker should not feel supervised and/or tracked.

Robustness:

- The system should be robust enough to not create a stop in the production.
- The system should be robust enough to operate in an industrial environment.
- The system should not be manipulable by the operator.

Cost: The cost of the tracking system is important however it is not a constraint for the state of the art.

Scalability: The system should be easy to install/remove/change, however it is not a constraint for the state of the art.

Dimension: A possible add-on to the tool should not affect the usage significantly. The size and weight of the add-on should preferably be of similar dimensions as the current add-ons.

1.3 Scope

In this report a pre-study to above specified requirements is presented. The report includes state of the art, both for unmitigated techniques and for techniques that require some sort of sensor fusion or combination. The study only looks at the techniques that are for indoor positioning and localisation.

1.4 Method

The techniques are evaluated using an advanced decision matrix. This technique is introduced by Pugh.[1] In order to evaluate the techniques, the requirements are weighed against how hard or important they are, the sum of the weighing factors is one. Thereafter the techniques are scored a number between zero and one by the authors of this report. The scoring is done on two parameters. Firstly, confidence on the system satisfying the requirements and secondly, knowledge of the system. The scoring by the authors and the weighing factors are then factored and the average of the scoring decides the final scoring for the technique.

2 State of the Art

In this section the current state of the art in indoor positioning will be presented. Both basic technologies that could be used to solve the problem and complete commercialised, solutions will be presented.

2.1 Vision

There are three identified techniques for positioning with vision. They are Camera on Tool, Stereo Vision and Time of Flight cameras. This section includes these three techniques and one more, Structured Light, which is a combination of cameras and projected light patterns.

2.1.1 Camera on Tool

Visual odometry (estimation of change position over time) is the process of estimating the position and orientation of an agent (e.g., vehicle, human or robot) using only the input of one single or multiple cameras attached to it. [2] The relative position error of visual odometry with a single camera is about 1.2 percent on a 20 m path. Stereo visual odometry provides more accurate trajectory estimates, with relative position error ranging from 0.1 to 2 percent. [2] The accuracy is up to 2 cm, which is given by David Nister. [3] Small vision sensors are quite cheap, less than 50 USD for single pieces. The possibility to implement this technique in a rough environment is low. Rapid movements and obscured camera views are two big challenges.(Mårten Björkman, pers. comm.) The robustness issues should be taken into consideration. This technique is used on NASA Mars Exploration Rovers. [4]

2.1.2 Stereo Vision

Stereo vision is a method to compute a 3D-Object from two or more images. The images must be of the same object, from different viewpoints. [5] The distance between the cameras and the object can be calculated by observing the pixels that corresponds to the same point in the 3D-object. The point can be calculated in a 3D space, by knowing the focal length of the cameras, baseline and view angle. [6]

There are mainly two possible usages of stereo vision. These are stereo vision cameras mounted on the tool or cameras mounted in the environment. Stereo vision cameras mounted on the tool is not applicable for this particular problem since the size of add-ons on the tool is limited. Furthermore the stereo cameras need a baseline that will be too long to function properly and motion blur will be a problem. It's hard to implement this in a rough environment.

Cameras mounted in the environment is promising. More than one camera can cover a bigger area and can follow one or more tools at the same time. Stereo vision could be used in the environment as a global indoor positioning system to give a rough position with around 2000 mm accuracy. With this technique, we can also get a more accurate zone positioning less than 5 cm. It updates at more than 10Hz, which fulfil our requirements. [7] The cost depends on the amount and quality of the cameras, but normally it is not expensive. The focal length and the actual distance to the target determine the accuracy which can be achieved less than 5 cm. Also, it can fulfil the implementation in a rough environment. The drawbacks of the technique are that line of sight is needed and that the target may be blocked by the operator. However, this technique, with other techniques combined, can be very useful in the project.

2.1.3 Time of Flight

Time of flight uses a method where it sends out a laser pulse, and measures the time it takes for the pulse to bounce and come back. By knowing the speed of light, the distance can be calculated. A 3D ToF camera works by illuminating the scene with a modulated light source, and observing the reflected light. The phase shift between the illumination and the reflection is measured and translated to a distance. [8]

The company Mesa Imaging uses the time of flight camera for positioning. [9] A fully packaged industrial product, the Mesa 4000 and 4500 costs about 4500 USD, although, it could be built from scratch to a cheaper price. The resolution of this technique is about ±2 cm at 0.5-5 m, with a measuring distance of 0-9 m. [9] The product is feasible to implement in a rough environment. However, after talking with Patrik Jensfeldt(Patrik Jensfeldt, pers. comm.), this technique does not seem very promising, since there will be problems such as motion blur, pointing the camera in a relevant directions and blocking of camera. Besides this, if the camera is aimed at very smooth surfaces, like metal, the light will bounce straight off, since it will not scatter.

2.1.4 Structured light

Structured light is the process of projecting a known pattern onto a surface, then by using a vision system record the displayed light on the surface. By observing the distortions, the depth and surface information can be calculated. From this a 3D-model can be created which in turn is possible to use to calculate a distance . [10] Structured light is often used as active triangulation, because it has one structured light-source and one camera. Infrared light, laser or a normal video projector can be used as structured light. To use structured light mounted on the tool and then record the target area can be a technique that could solve the problem. [11]

The cost of this technique starts at 500 SEK, which is very cheap. The best accuracy of this technique is less than 0.01 mm. [12] The possibility to implement in rough environment is medium. A problem will be that if the tool moves a lot, the system will be influenced and become inaccurate.

2.2 Light

This section contains short information about different positioning techniques which utilises some kind of light.

2.2.1 Laser - Time of flight

Time of flight lasers works by sending out a laser pulse, which reflects against an object in the environment and the time of the arrival of the return pulse is converted into a distance. There are systems which can give an accuracy of 9 μm [13], but they are expensive. Time of flight is also used in laser measurement units in construction and it is possible to get a laser measurement with a better accuracy than 1 cm for less than 500 SEK. [14] Laser measurement units are used in construction sites and are robust enough for an industrial environment. The technique has no latency of measurements and can be run at a higher frequency than 10 Hz. The downside with the technique is that it is only possible to measure in one dimension, requires a very good temporal accuracy, requires line of sight and can easily be manipulated by covering the sensor.

2.2.2 Laser - Triangulation

Triangulation with lasers can be done by sending a laser beam towards an object. When the reflected beam returns it is captured by a lens which focuses it and causes it to hit a very precise point of a sensor. The distance depends on where the laser hits the sensor. With this technique accuracies down to 0.04 μm can be achieved depending on the work range used. Typically distances between 2 - 1250 mm are measured. [15] The measurements does not have any delay and can be updated more frequently than 10 Hz. The laser triangulation systems are robust, extremely accurate and built to work in industrial environments. The downside with the system is that it is expensive and, gives only a one point measurement and it can easily be manipulated by covering the sensor.

2.2.3 Visual light communication

Visual light communication utilises image sensors and planted light sources to triangulate the position of an object. The light sources are used as reference points for the the optical receiver. Each LED has its own ID which is represented by a binary code which is broadcasted by switching the light on and off with high frequencies. There are several different ways to triangulate the position but the one which have achieved the highest accuracy is triangulation by signal strength. [16] Another benefit with RSS (Received Signal Strength) is that there is no need for synchronisation between the transmitters (light sources), which also makes it easier and cheaper to deploy the system.

The LED:s are inexpensive and a regular off the shelf LED can handle the switching frequency required. The photo sensor can be bought relatively cheap as well (a common mobile camera is enough). The best physically measured accuracy achieved is 0.651 cm (RMS of the error). [17] This accuracy was measured in 2D and not 3D (height was known). It is possible to measure in 3D but simulations in other articles indicate that the noise tolerance decreases and the mean of the positioning error increases [18] to almost the double in 3D.

The technique is very interesting since it offers higher bandwidth capacity than radio based solutions. It is also robust to electromagnetic interference, has an excellent security and does not cost much to install. [19] The problems with the technique is that it suffers from shadows and reflection. There are also problems with the angle of the photo sensor and that the system is very easy to manipulate. The system might also be of interest for less accurate position estimations. [19] There is at least one commercial system which utilises the technique in combination with mobile camera, IMU and bluetooth signal strength to track people in a store. [20]

2.2.4 Projected IR light

The Optotrak Certus system is able to have an accuracy of 0.1 mm at a range of 7 m. [21] [22] When combined with active markers, which is basically IR light sources, it can track 6 DOF wireless when in line of sight. This is a high end research level system and it is quite expensive.

The well known Kinect system from Microsoft is based on IR light technology where there is one IR emitter that sends out light and one IR Depth sensor which captures the depth of a 1280 x 960 grid which creates a point cloud. Even though this sensor is considered cheap, it is quite potent in accuracy. [23] The problem compared to the other Time of Flight cameras is that it is not designed to work in a industrial environment. Khoshelham and Elberink [24] measures and evaluates the resolution and accuracy of the Kinect, and it was concluded that it should not be used at a longer range of 3m, since it will have too big random measurement errors and too long distance between the points. The accuracy is roughly between 0.1 cm at 50 cm to 1.5 cm at 300 cm.

2.3 Sound

Sound is a mechanical wave that travels through air or other media which theoretically makes it possible to use in a non-line of sight (NLOS) situation. Techniques used today most commonly use sound waves in the spectrum of ultrasonic sound, although, solutions using audible sound also exists.Techniques using audible sound are not feasible in our situation since it would be uncomfortable for the operator.

Techniques or algorithms used for sound positioning are Time of Flight (ToF), Time difference of arrival (TDoA), Angle of arrival (AoA) often referred to as Triangulation, Extended Phase Accordance Method (EPAM) or Sonar.

Ultrasonic solutions create a cheap alternative to other positioning systems, it is capable of generating high accuracy and, as mentioned earlier, capable to work in a NLoS situation. The downsides of the techniques are first and foremost the decay profile of sound, reflections in environment and sensitivity to background noise. Depreciation due to the spherical diffusion of sound waves makes this technique limited to a distance of 10 m. [25] In an industrial environment there are plentiful of sources generating ultrasonic noise and specifically in environments using air tools where noise levels can be as high as 100 dB [26], decreasing the range of use further. Other downsides are the sensitivity to change in temperature (this is often solved by using temperature sensors on transceiver and receiver, although temperature between them are not possible to measure) and a rather long response time, at worst 10 Hz due to the speed of sound. [25] One last aspect to consider is the working environment for the user of the tool we need to position. There are several guidelines regarding exposure levels, e.g. "...the Canadian 1991 [...] recommendations give 110 dB SPL as the maximum level for occupational exposure in a 1/3 octave band centered on 40 kHz". [27] Ultrasound affects the user and especially if the transceiver is placed at the tool (which means close to the user) the sound levels are restricted.

2.3.1 Angle of Arrival

One of the most interesting solutions for this project are the AMT Ultrasonic add-ons. These are basically a product able to position a tool in an industrial environment. In the datasheet for their product they claim to have "exact positioning" and by judging the branding; down to mm accuracy. [28] They use triangulation (Angle of Arrival) to position the tool. This is a product built for same situations as this Tooltracker project and use almost identical conditions as defined in our requirements (with exception to technical details about accuracy, which is not possible get to know from the datasheet).

2.3.2 Time Difference of Arrival

Wendeberg et al. (2011) [29] conducted a project using the TDoA method and they were able to reach an RMSE accuracy of 2.5 cm by using their own non-linear "Cone Alignment" algorithm. In order to use this technique they needed to be able to synchronize the receivers up to an order of 0.1 ms. They have tested their system in real world situations.

2.3.3 Time of Flight

The MIT cricket system [30] is a system solution where beacons are used to send ID and data. This is made trough ultrasound and radio to get an ID and time-stamp, making the receiver (the dynamic target) able to make a distance calculation to every transceiver. This is a very scalable system with sub 10 cm accuracy at 8 m and about 1 cm at 2 m (depending on the angle). The orientation accuracy was under 3 degrees between -60 to 60 degrees for the angle between the perpendicular to the receiver array and a beacon.

The Active Bat prototype [31] from 1997 uses a similar technique as the Cricket system. They claim to have an accuracy of 3 cm and do this by setting up a grid of ultrasonic receivers in the ceiling with a distance of 1.2 m. They then measure the ToF from the transceiver. Harter (2001) [32] uses a similar solution which by improvements of new transducers reaches resolutions under 1 cm. These systems in combination with the cricket system might form a promising solution.

A variation of this is tested in the Teliamade system [33], where an ultrasonic transmission is used to calculate time of flight and a zigbee module is used to communication information between the nodes. The next step after that system is to use MEMS based sensors that are intrinsically omnidirectional and have greater range.

One last company working with the ToF method is Hexamite. [34] By using a ToF calculation in arriving signals and by looking at the doppler effect it is possible to calculate both position and velocity of the transceiver. They claim to have a precision of the system of 2 mm in their HX19V3 system. [35] This is an interesting ready-made product that is possible to buy and test for validity in our case. The price of a system is around 1500-2000 euros depending on the components.

Liu [36] predicted in 2007 that one future trend is the combined solutions for indoor positioning with ultrasound. How to combine them into a practical system is a topic of sensor fusion. In Table 1 some companies using sound for positioning are presented. A more extensive table from 2012 could be seen in Indoor positioning technologies [7] at page 56 and from 2007 in a survey of wireless indoor positioning techniques and systems [36] at page 1077.

Company name	Year	Reported Accuracy	Principle	Application
AMT UltraSonic	2013	"exact positioning"	AoA	Product
Wenderberg et al	2011	2.5 cm	TDoA	Prototype
Cricket	2005	1-2 cm	ToF	Product
Teliamade	2013	9.6 mm	ToF	Research project
Hexamite	2011	0.2 cm	ToF	Product

Table 1: Companies using sound

2.4 Radio

Radio-based positioning techniques, such as those employed by cell phones, WiFi, and Zigbee are some of the most commonly used positioning techniques due to their relatively high transmission power and the requirements of dedicated devices. The positioning methods used in radio-based techniques can be broadly listed as:

1. Cell of Origin(CoO)
2. Angle of Arrival(AoA)
3. Time of Arrival (ToA) or Time Difference of Arrival (TDoA)
4. Received Signal Strength(RSS) based trilateration
5. Location fingerprinting

A typical RFID system has three components: a transponder or tag (located on the object to be tracked); an interrogator or reader (which receives the information from tags); and a control unit (which operates the system and processes the information). The basic idea of the RFID technique is to transfer the information of identification from an electronic data-carrying device - the RFID tag - to an RFID reader via a RF interface. The technique can be classified into two systems - passive and active - depending upon the signals transmitted and the tag structures. A passive RFID tag contains very simple components to respond with its information of identification to the signals triggered from a RFID reader. It does not contain an electronic power source itself. The energy for the RFID tag's circuit is transmitted from the RFID reader via magnetic or electromagnetic fields over a short range (less than 3 m). Its reading range is limited by the range of energy transition. In contrast, active RFID tags have a longer reading range (over 15 m) due to built-in batteries. In positioning applications, RSS is the major observation component in RFID systems. It is used to determine either the appearance of a mobile user in the reading range or the distance between transmitters and receivers. [37] In Table 2 below a summary of companies using radiowaves for positioning is presented.

2.4.1 Ultra-wideband

Ultra-wideband (UWB) is a radio technology for short range, high bandwidth communication holding the properties of strong multipath resistance. To some extent also used for its penetrability of building material which can

Company name	Year	Reported Accuracy	Type	Principle	Application
Utchitomi	2010	20 cm	Passive	CoO + AoA	Simulation
Fujimoto	2011	15 cm	Passive	CoO + Range	Study
NaviFloor	2011	50 cm	Passive	CoO	Product
Baum	2007	100 cm	Passive	CoO	Development

Table 2: Companies using Radio

be favourable for indoor distance estimation, localization and tracking. A typical UWB setup features a stimulus radio wave generator and receivers which capture the propagated and scattered waves. In contrast to narrow-band operation, UWB waves occupy a large frequency bandwidth (>500 MHz).

The low power spectral density prevents harmfulness to the human body and bounds the interference of UWB signals with other narrowband receivers. The low frequency components in the UWB signal spectrum have the ability to penetrate building material such as concrete, glass and wood [38]. This is a useful property for indoor positioning, because it enables ranging under NLoS conditions and makes inter-room ranging possible. On the other hand, partial signal penetration into the target object is unfavourable for precise distant measurements, because the reflected signal includes multiple returns besides the outer boundary reflection. Therefore robust extraction of useful information from the received signal is a major challenge in UWB ranging. Superposition of different scattering effects complicates the data interpretation. [7] In Table 3 below some companies using UWB for indoor positioning are presented.

Company name	Year	Reported Accuracy	Type	Principle	Application
Ubisense	2011	<15 cm	Active	TDoA, AoA	Product
Zebra	2011	<30 cm	Active	TDoA	Product
TimeDomain	2012	2 cm	Active	ToF	Product
decaWave	2010	<10 cm	Active	TDoA	Product

Table 3: Companies using UWB. Note that the accuracy listed is in LoS.

2.4.2 Wi-Fi trilateration

A transmitter send out a Wi-Fi signal and a receiver collects the signal and based on the signal strength determines the distance to the transmitter. A distance between the transmitter and receiver can be calculated by comparing a RSSI value and a function curve that describes signal strength versus distance. By having multiple transmitters in an area, the position of the receiver's position can be predicted. In Table 4 some examples of existing system using Wi-Fi trilateration are presented.

Company name	Year	Reported Accuracy	Type	Principle	Application
Navizon	2015	3 cm/m	Active	RSSI	Product
Ekahau	2015	3 cm/m	Active	RSSI	Product

Table 4: Companies using Wi-Fi trilateration.

2.4.3 Wi-Fi fingerprinting

A radio map is created by measuring the RSSI data from several transmitters in an area. Probability distributions of RSSI Values is generated by the data, that corresponds to a given positions in the area. By measuring RSSI and comparing it to the fingerprints, a position can be predicted for the receiver. In Table 5 some examples of existing system using Wi-Fi Fingerprinting are presented.

Company name	Year	Reported Accuracy	Type	Principle	Application
Indoors	2015	$<$5 cm/m	Active	RSSI, Fingerprint	Product
WiFiSLAM	2013	2.5 cm/m	Active	RSSI	Product

Table 5: Companies using Wi-Fi Fingerprinting.

2.4.4 Bluetooth trilateration

RSSI signals from Bluetooth beacons with unique signature. The beacons positions are known locations in an area. The receiver uses triangulation to calculate its position.

2.5 Inertial Measurement Unit

An inertial measurement unit, IMU, is a gyroscope in combination with an accelerometer. [39] [40] The accelerometer is able to measure the acceleration in the three axes of the IMU body frame, and the gyroscope measures the angular rate of rotation in three axes. [41] Best accuracy possible is time dependent because of the quadratic growth in position error due to double integration of acceleration data containing bias and drift errors, [42] [43] [44] but is very accurate in short periods of time and the accelerometer can be reset and the error can be bound in moments of zero velocity. There are also techniques to find out the sources of error for an accelerometer: bias, drift, non-linearity etc. It can also be integrated with other methods for binding the error further. The best accuracy feasible with smaller gyroscopes is 0.3 deg/root-hour with 0.1-1 accelerometer bias. [45] This information can be used to estimate and bind the error. The estimated price of this technique is 100-5000 SEK.

2.6 Magnetic

Magnetic localisation techniques uses artificially made magnetic fields. It could either be permanent magnets, AC fields or DC field and the localisation is achieved by having several sources of magnetic fields and then using a triangulation technique for finding the position and the attitude of the source as described in. [46] The problems this technique faces is that when ferromagnetic materials is close to the sensor, the sensor picks up on the material which disturbs the measurements. There has been some work done to map and reduce this noise at Stanford University. [47]

2.6.1 Artificial AC magnetic field

The system called G4 [48] is a wireless localisation system using AC magnetic fields, the system is developed by Polhemus. It has a reported accuracy when in LoS of a few milimeters in a 6 DOF with a working area of 1.5 m, which in turn could be added on to about 5 m depending on the amount static sources that is used. This technique has the advantage of working in NLoS situations, with some loss of accuracy, but the loss of accuracy is still below 5-10 cm depending on what materials that obstruct the view (if it is not a ferromagnetic material).

2.7 Hybrid Systems

2.7.1 Sensor fusion with UWB, IMU and a dead reckoning system

In Sillero's masters thesis [49] a number of sensor fusion algorithms using Kalman Filters and Particle Filters are developed to improve the localisation accuracy for a mobile robot. Based on simulations it was concluded that the sensor fusion algorithms significantly improved the localising performance over the individual systems, and accuracies around 4-5 cm was achieved. However when trying the algorithms in a real environment with a Ubisense system and an IMU the performance did not improve significantly over the Ubisense system itself, which had an accuracy of about 40 cm. The conclusion from that experiment was that the IMU used was too inaccurate to provide any improvements to the Ubisense system. This study still shows that using sensor fusion might be a good approach to solve the problem.

2.7.2 Systems based on sensor fusion without beacon instrumentation

Bhuiyan et al. [50] conducted a study about indoor positioning for a mobile robot without beacon instrumentation. Sensor fusion algorithms with Kalman Filters using WiFi signal strength and IMU:s as sensors was developed. The accuracy that the sensor fusion algorithms achieved was about 2.9 m with a standard deviation of 2 m.

A commercial system with a similar approach is a system called NEON, developed by TRX Systems, for indoor 3D positioning. NEON tracks persons in GPS-denied areas by fusing measurements from different sensors like IMU, pressure, light and Time of Flight RF ranging. The system is based on TRX:s SLAM algorithm FeatureSLAM and operates without beacon instrumentation. The typical accuracy for NEON is 3-7 m. [51]

These systems are included in the State of the Art to show what kind of accuracy that is reasonable to get with a completely mobile system without any infrastructure installed.

2.7.3 CLIPS

Tilch and Mautz invented a system called CLIPS [52], which stands for Camera and Laser based Indoor Positioning System. CLIPS utilises fusion of lasers and cameras to determine the position. It uses one camera and a device that project several distributed laser spots. This is used as a reference frame. With this they can reduce the computational costs, because they only use one camera. The system is also mobile since the device creates its own reference frame. The standard deviation in one axis, for one measurement, was about 0.2 mm. During what distance this measurement was made is unstated in the article. But they claim to have a deviation of about 2 mm/m.

2.7.4 FARO

ABB uses a system called FARO laser tracker which utilises a Time of Flight laser. The system returns the 3D position of the object with a measured resolution of 0.009 mm at distances up to 3 m. The system uses the distance measurement combined with with the angle of the laser to achieve this. FARO can locate its target with the aid of cameras and uses a sphere-mounted reflector to bounce the laser back. The downside with this technique is that it requires line of sight, has a limited angling span of the sphere mounted reflector and is extremely expensive. [13]

2.8 Summary and Comparison

A summary of the techniques can be seen in A Appendix. You can see an overview of how the different techniques fulfil the requirements set in the introduction. It can be noted that the unit measurement differ between the techniques, this is kept in this way because the implicit increasing or subtraction of accuracy this can give if changed. The same can be said for the currency displayed, the exchange rate and the difference market (and shipping) might give a false value if changed to only one currency.

3 Discussion

3.1 Advanced Decision Matrix Evaluation

In Summary and Comparison of the state of the art techniques (A Appendix) you can see an overview of how the different techniques fulfil the requirements set in the beginning of the report. In order to evaluate this summary of the noteworthy techniques, firstly the requirements have been weighed against how hard or important the requirement is (see 1.4 Method), results are presented in Table 6 and the indivudiall scoring can be seen in (C Appendix).

Requirement	Scoring
Accuracy of 10 mm when at a distance of 600 mm or less from targets	23.75
The system should be robust enough to be able to operate in an industrial environment and the system should be robust enough to avoid causing stop in the production	15
6 degree of freedom output	13.125
Accuracy of 500 mm inside a work space and accuracy of 2000 mm when in a global indoor positioning system	9
Position update with a frequency of minimum 10 Hz	8.625
The system should not be able to be manipulated by the operator	7.75
The systems position lag shall not be greater than 200 milliseconds	7.625
Worker should not feel supervised and /or tracked	5.25
The size	4.875
and weight	3.625
The cost of a tracking system	1.375

Table 6: Requirement scoring, higher scoring means higher importance of the requirement.

Thereafter the different techniques have been scored by the authors of this report (see 1.4 Method). The results of this can bee seen in Figure 1 and Figure 2. Techniques that clearly aren't suitable for the requirements are left out of this comparison. As well as IMU as it is time-dependent and also regarded by the authors of this report as a complementary technique to deal with non line of sight (seperate section below). The promising techniques according to the grading given by the authors of this report (see Figure 2) are Ultra-wideband, time of flight sound, stereo vision, triangulation and angle of arrival of sound, time difference of arrival sound, time of flight laser, FARO, and UWB, IMU dead reckoning. Where only Ultra-wideband, stereo vision, FARO, and UWB, IMU dead reckoning are able to give a position with six degrees of freedom. Stereo vision can give an accuracy below 5 cm, which means that it may be a good candidate to solve the problem, maybe in combination with another more accurate (but maybe one dimensional output) technique. The sound techniques has shown to have at least a medium robustness in industrial environment, which might seem like a problem initially, however, these techniques still will not get down to the accuracy given in the requirements as will not the hybrid system UWB, IMU and dead reckoning.

However, the ranking of these systems might be dragged down by the authors knowledge, in Figure 1, it is also clear that the confidence in the magnetic field and the Projected IR light is high, which both have mm precision and can measure 6 degrees of freedom.

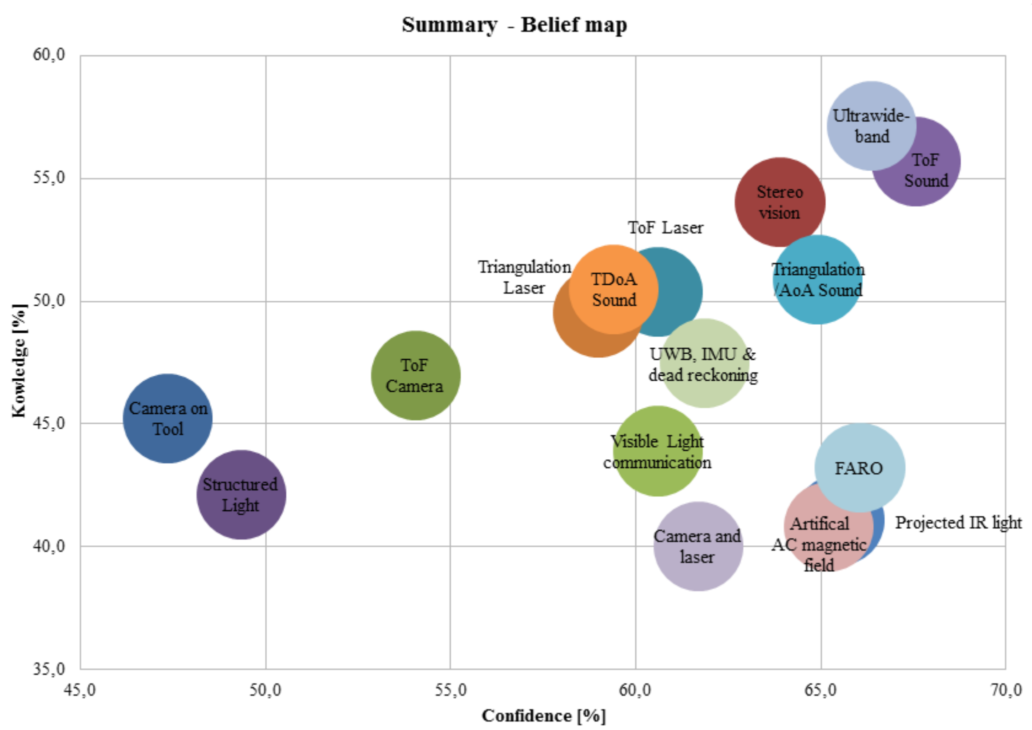


Figure 1: Summary of the authors' confidence and knowledge regarding the different techniques

	Satisfaction Score [%]
Ultrawideband	40,1
ToF Sound	38,8
Stereo Vision	36,1
Triangulation/AoA Sound	35,1
TDoA Sound	32,3
ToF laser	32,3
FARO	31,7
Triangulation Laser	30,6
Projected IR light	29,9
UWB, IMU & Dead Reckoning	29,4
Artifical AC Magnetic Field	29,3
Visible Light Commmunicaition	29,2
ToF Camera	26,6
Camera and Laser	26,0
Structured Light	22,3
Camera on Tool	22,1

Figure 2: Summary of the authors' satisfaction regarding the different techniques

In the summary it can be seen that some of the systems does not fulfil the requirement of intrusiveness, however, this is a subjective experience and therefore, if these systems show a lot of potential, they should be evaluated further with a focus group (or similar). The individuall scoring of each technique can be seen in (B Appendix).

3.2 Non Line of Sight

In the requirements it can be seen that line of sight is not evaluated as a criteria. However, that the system loses line of sight is a very possible situation, therefore systems that fulfil this criteria is interesting to consider. The systems that still work without line of sight is IMU, Ultra-wideband, magnetic systems like G4, time of flight camera and camera on tool. The IMU have the advantage of working without any fixed references but the gyro will drift. Usually the gyro is reset, but in order to do that the tool has to be still, which can be problematic. The gyro might instead be gradually corrected which can be done by different methods and help from other techniques. Camera on tool and time of flight camera may have problems when it is directed towards something it does not recognise, for this to work best it should be moved slowly and steadily. How it would work on a handheld tool is something that needs to be evaluated, but as can be seen in the scoring, camera on tool has the lowest satisfaction score and time of flight camera has a lower scoring as well. The magnetic solution does not have a very high satisfaction score, it scores very low on robustness, as in an industrial environment it would be a lot of disturbances from the tools in the factory. The Ultra-wideband, however, scores the highest of all the systems, however it does not fulfil the accuracy (best is 2 cm).

3.3 Accuracy Comparison

Accuracy comparison of the investigated techniques can be seen in Figure 3 below where the requirement of 10 mm is marked by a red circle. The most accurate of these techniques is FARO and laser - time of flight, shortly followed by vision - structured light. However FARO is very expensive with an satisfaction score of 31.7 (see Figure 2), which is medium. Time of flight laser only has one dimensional output but is ranked as a top choice and the structured light might become inaccurate depending on how the operator moves the tool and is therefore ranked very low. Most of the techniques do not work without line of sight but is very advantageous in other aspects and combined with a non line of sight technique can create a system that will work in many situations.

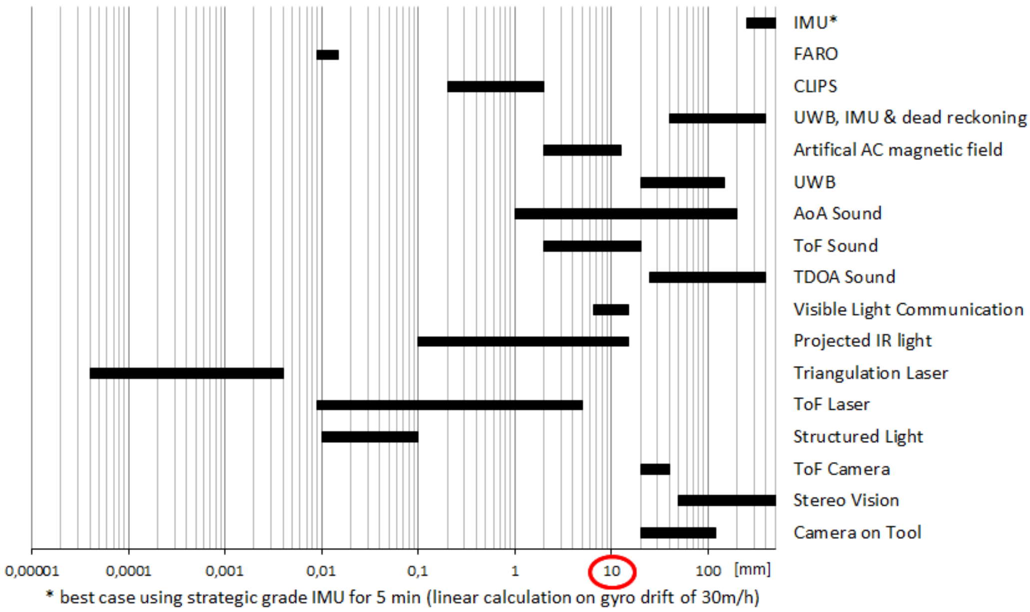


Figure 3: (Logarithmic) Accuracies for different techniques [mm]
* best case using strategic grade IMU for 5 min

3.4 Conclusions from the State of the Art Evaluation

The conclusion that can be given is that if a system shall be developed with the kind of precision that are stated in the requirement, there will be a higher risk of project failure. However, there is a clear possibility of being able to build a system with about 5 cm accuracy.
And as can be seen by the evaluation, building for a different requirement of accuracy is an entire set of techniques. However, the goal can perhaps be reached by easing another requirement. To change the accuracy requirement might make this pre-study invalid.

4 Proposed solutions

In this section a general system design that could solve the localisation problem and four idea concepts that incorporates different technologies will be presented. The concepts were developed at a brainstorming session.

4.1 System design

The proposed system design is based on fusion of different sensors that are suitable for different categories of localisation. By using sensor fusion with e.g. a Kalman Filter a better estimate of the system state can be achieved than from using the sensors individually. The categories of localisation considered are:

- Global positioning
- Local positioning
- Non-line of sight positioning

Global positioning would provide a rough estimate of where the tool are within the factory with a sub-meter accuracy. Ideally this would work both with and without line of sight. The most suitable technology for this is Ultra-wideband, but vision and sound could also be used. Local positioning would provide an accurate position with less than 1 cm error within the work station. For this, technologies such as external vision, lasers and sound could be used. Because of the environment where the tool will be used, non-line of sight positioning is also needed. For NLOS positioning IMU:s and cameras mounted on the tool could be used.

4.2 Concepts

Here the four brief concepts generated at a brainstorming session will be presented. The concept are preliminary and may not all be possible to build in reality or may be very hard to implement. The concepts will not be evaluated in this report since they were generated before the scoring of the different technologies was performed. They are presented only to give an estimate of what a prototype could look like.

4.2.1 Concept 1

The first concept uses UWB for global positioning, an external vision system that detects two light stripes on the tool for accurate local positioning and an IMU for local positioning, see Figure 4. By detecting the light stripes with more than one camera and by knowing the geometry of the stripes the pose of the tool could easily be calculated. The light could be non-visible to the human eye to not cause any distractions to the workers and the external vision system could filter all other wavelengths so the workers wouldn't feel supervised.

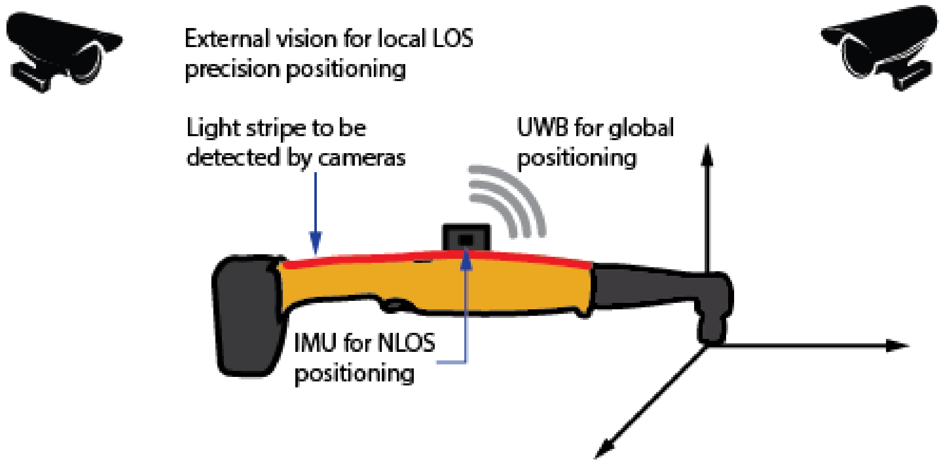


Figure 4: Concept 1

4.2.2 Concept 2

The second concept, see Figure 5, uses sound localisation for accurate local line of sight positioning. This concept assumes that a map of the environment is known and that the IMU can be calibrated at every bolt to reduce drift. The IMU will handle all non-line of sight positioning. It assumes that sound localisation and IMU provides sufficiently good accuracy for global positioning when fused.

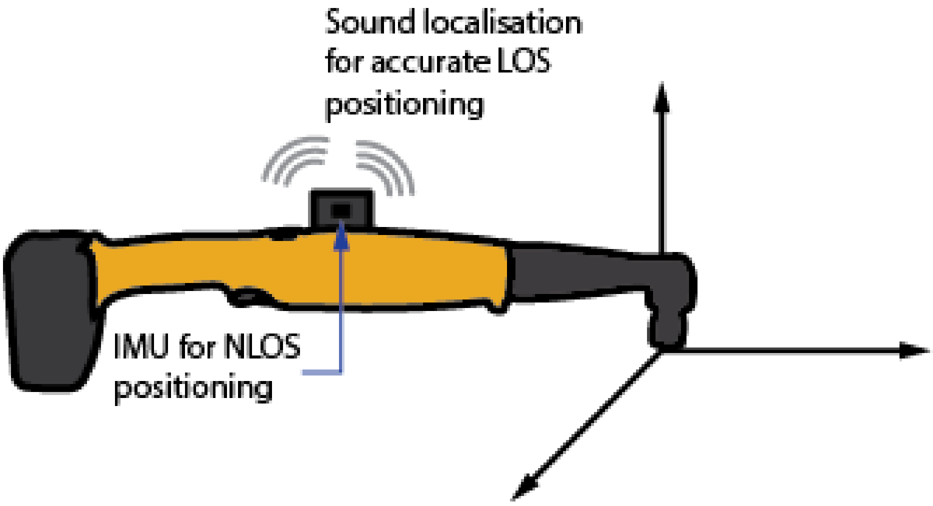


Figure 5: Concept 2

4.2.3 Concept 3

The third concept, see Figure 6, uses UWB for global positioning and an IMU for non-line of sight positioning. It uses a Time of Flight camera that matches its output to a map for local positioning. The ToF camera would also work without line of sight, which improves local NLOS positioning.

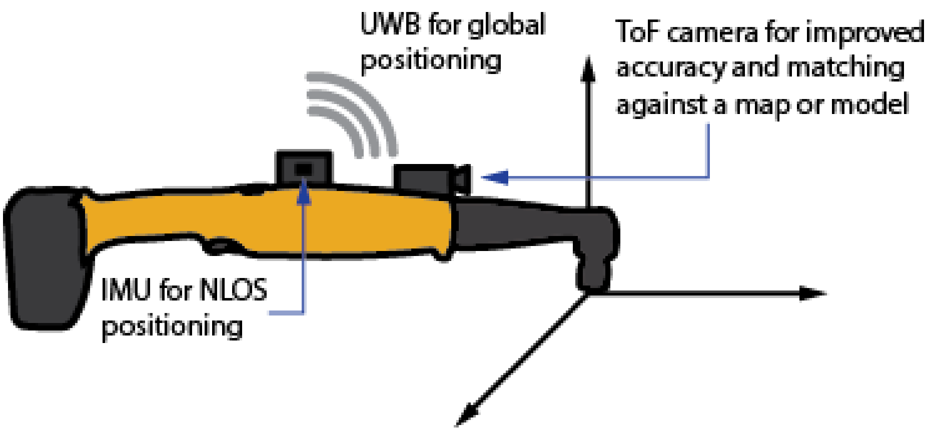


Figure 6: Concept 3

4.2.4 Concept 4

The fourth concept, see Figure 7, uses an external vision system for global and local positioning and an IMU for NLOS positioning. The time of flight laser is used to generate a very accurate position when it detects the tool.

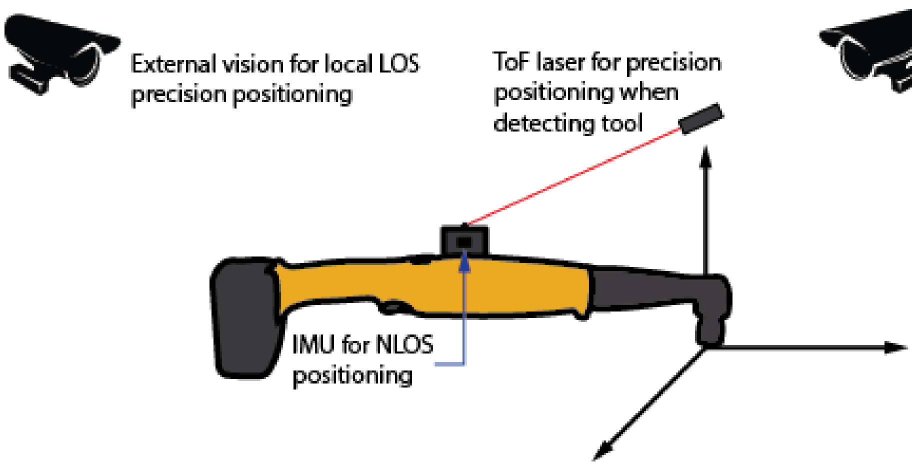


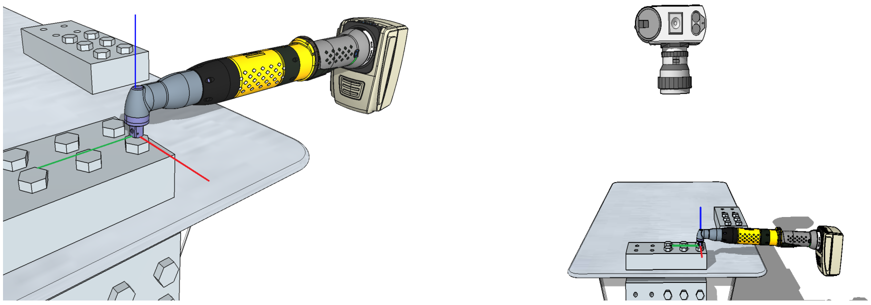
Figure 7: Concept 4

4.3 Testing

To be able to verify that the system meets the accuracy requirements, a two part process has been chosen. In order to facilitate rapid testing a simple test will first be used which will be further developed.

The first test concept is three or more blocks with threaded holes, see Figure 8a which have fixed geometry and will be machined with sub millimetre accuracy. Using a table and machined fixtures these boxes and a origin point are mounted in a special pattern to test a few common mounting scenarios taken from the industry. The origin point is a stand for the tool to be calibrated and reset. The gathered data will then be compared with the known geometry.

The second test concept is supported with a high-speed camera, see Figure 8b, for the ability to verify the tracking in 2D. These two data sets are synced with a led which is turned on from the switch and its state is also logged to the system collecting the test data. In this way testing of the human reaction time can also be verified.



(a) First test concept (b) 2D tracking

Figure 8: How to verify the position

4.4 Stakeholders

These are the identified stakeholders.

4.4.1 Stakeholder identification

- Atlas Copco
- The customers (Eg. Scania, Volvo)
- The operators
- The service technician

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A Appendix

Technique		Accuracy	Difficulty of manipulation of system	Update freq >10Hz	Pos lag of sys <200ms	6 degrees of freedom positioning	Pos tool <500 mm accuracy
Vision	Camera on Tool	2 cm	Motion blur will occur with extensive movement.	Can probably be met.	Can probably be met.	Yes	Yes
	Sterio Vision	Less than 5cm, can be very good	Targets may be blocked by operators	Yes	Can probably be met.	Yes	Yes
	Time of Flight Camera	2 cm	Motion blur, blocked by some objects	Can probably be met.	Can probably be met.	Yes	Yes
	Structured Light	Less than 0.01mm	Inaccuracy wit a lot of movement	Can probably be met.	Can probably be met.	Yes	Yes
Light	Laser - Time of Flight	~0.5 cm, can be 0.009 mm	Can cover the sensor.	Yes	Yes	No, 1 dimension measurement	Not alone
	Laser - Triangulation	0.04 µm	Can cover the sensor	Yes	Yes	No, 1 dimension measurement	Not alone
	Projected IR light	0.1 mm	Can cover the sensor	Yes	Yes	Yes with 3 markers	Yes
	Visable Light Communication	~0.6 cm	Can cover the sensor	Yes	Yes	Hard with sensor placement	Yes
Sound	Time Difference of Arrival	2.5 cm	Maybe by covering the transmitter	Yes	Yes	No, only position	Yes
	Time of Flight	0.2 - 2 cm	Hard/Medium	Yes	Yes	No, only position	Yes
	Angle of Arrival - AMT Ultrasonic	"Very exact"	Hard	Yes	Yes	No, only position	Yes
Radio	Ultrawideband	Best 2cm (line of sight), avg 15cm	Hard	Yes	Yes	Possble	Yes
Magnetic	Artifical AC magnetic field	Few milimeter	Medium	Yes	Yes	Yes	Yes
Hybrid Systems	UWB, IMU & dead reckoning	4-5 cm (simulation) / ~40 cm (experiment)	Hard	This can probably be met.	This can probably be met.	2dof, can probably be extended	Yes
	CLIPS	Deviation is about 2 mm/m	Medium	This can probably be met.	This can probably be met.	Yes, with line of sight	Yes
	FARO	0.009 mm	The reflector may be covered.	Yes	Yes	Yes with IMU, requires LoS	Yes
IMU	Inertial Measurement Unit	0.3 deg/root-hour drift for gyroscopes. 0.1-1 Accelerometer bias. Strategic grade IMU ~30 m/h drift. Navigation graded gyroscopes 0.005 deg/root-hour drift.	If the unit is shaked heavily, the accelerometer will get very incorrect readings.	This can probably be met.	This can probably be met	Yes	Timedependent, see accuracy

Price	Robustness in industrial environment	Size of system	Weight of system	Intrusiveness		Technique
50 $	Low			Intrusive	Camera on Tool	Vision
Depends on cameras	Good	Can be big	Can be heavy	Intrusive	Sterio Vision	
4500 $	Low			Intrusive	Time of Flight Camera	
500 SEK	Medium	Can be large or can be small on the tool		Not intrusive	Structured Light	
500 SEK, can be more	Good	32x27x15 mm	<20g	Not intrusive	Laser - Time of Flight	Light
Expensive	Good	76x74x26 mm		Not intrusive	Laser - Triangulation	
Expensive	Decent	Markers is only led		Not intrusive	Projected IR light	
~1000 SEK	Decent	Size of photo sensor		Not intrusive	Visable Light Communication	
Unknown, not very expensive	Medium/Good	Small (size of speaker)	Lightweight ~200 g	Not intrusive	Time Difference of Arrival	Sound
1500-2000 EUR for Hexamite system	Medium/Good	Roughly the size of matchbox	~200g	Not intrusive	Time of Flight	
Unknown	Medium/Good	Small (size of a speaker)	~50g	Not intrusive	Angle of Arrival - AMT Ultrasonic	
Unknown	Medium/Good	Ubisense - 83 x 42 mm, PulsON - 76 x 80mm	PulsOn - 58 g	Not intrusive	Ultrawideband	Radio
Unknown	Weak/Medium	~ 15x15x15 mm	Assume ~100g	Not intrusive	Artifical AC magnetic field	Magnetic
Ubisense + IMU	Low	Ubisense + IMU	Low	Not intrusive	UWB, IMU & dead reckoning	Hybrid Systems
Unknown, not very expensive	Medium	Camera + Lasers	Low on the tool	Might be intrusive	CLIPS	
Very expensive	Very good	Approximately a sphere with a 1 cm radius	<50 g	Might be intrusive	FARO	
100 – 5000 SEK Around 100 000 SEK for military grade gyroscopes (very large).	The unit is only affected by shaking, no ither element will affect it	They can be very large, however, we can easily find IMUs in the size-range we would need	They can be heavy, but we can easily fing lighter ones	None	Inertial Measurement Unit	IMU

B Appendix

	Elin			Satyajit			Linxuan			Stefan			Mathias		
	Confidence	Knowledge	Belief	Confidence	Knowledge	Belief	Confidence	Knowledge	Belief	Confidence	Knowledge	Belief	Confidence	Knowledge	Belief
Camera on Tool	48,7	45,0	25,2	56,2	43,3	24,0	52,8	34,8	16,8	62,3	56,0	35,1	32,8	34,5	12,1
Sterio vision	69,2	51,0	36,0	66,8	58,2	38,2	62,7	48,5	29,8	56,5	50,5	29,7	82,0	58,5	51,8
TOF Camera	50,3	47,3	22,2	66,3	56,5	39,6	56,9	48,1	25,7	55,0	57,6	33,4	42,6	29,6	18,7
Structured light	51,2	35,7	18,1	61,7	55,9	36,4	56,0	42,8	23,1	51,9	47,7	26,7	30,9	27,7	11,8
Time of flight laser	62,8	42,2	27,7	65,6	41,9	28,7	65,6	47,0	32,4	62,7	64,5	44,3	44,0	32,6	18,0
Triangulation Laser	60,5	51,8	29,8	58,2	31,4	20,1	70,1	47,2	35,1	62,4	56,8	39,6	37,4	30,2	13,2
Projected IR light	67,4	32,8	25,1	67,4	40,2	27,9	73,4	40,7	32,2	76,4	67,0	54,4	23,2	15,5	4,1
Kinect	57,4	37,5	21,4	51,3	62,9	32,7	60,4	41,5	24,6	60,2	60,6	38,0	45,9	41,0	23,6
Visable Light com	65,3	39,0	27,9	66,5	35,7	25,2	68,1	40,4	28,1	46,7	54,0	28,8	32,1	22,0	9,8
ToF	64,2	43,7	27,9	69,2	63,4	44,1	52,2	47,8	25,4	68,6	63,6	45,7	57,7	54,4	33,3
Triangulation and AoA	50,4	33,8	20,2	73,2	66,0	48,5	53,5	43,3	23,9	68,2	60,0	42,6	53,2	40,6	23,6
TDoA	43,1	30,7	13,8	69,5	67,9	47,4	52,6	49,4	26,2	60,1	59,1	38,2	45,7	40,3	21,4
Ultrawideband	58,5	29,6	18,8	79,0	75,2	59,9	53,4	43,5	22,6	57,2	61,7	37,9	81,3	56,9	46,6
Artifical AC magnetic field	68,2	36,5	25,1	60,3	22,4	14,0	68,3	36,1	25,2	75,4	70,4	56,8	33,5	17,0	7,0
UWB, IMU & dead reckoning	49,0	30,0	14,1	72,1	42,7	30,9	56,5	37,8	20,9	65,3	58,4	41,5	79,3	50,2	39,9
Camera and laser	63,7	23,1	17,2	66,5	41,6	27,5	56,0	41,2	23,6	65,6	55,4	38,5	46,4	43,5	20,5
FARO	71,4	40,0	29,0	71,2	37,2	27,2	67,1	41,5	29,2	76,1	72,3	59,3	24,0	16,4	4,7
		Avg Belief	23,5		Avg Belief	33,7		Avg Belief	26,2		Avg Belief	40,6		Avg Belief	21,2

	Michael			Björn			Tobias			Adam			Christoffer		
	Confidence	Knowledge	Belief	Confidence	Knowledge	Belief	Confidence	Knowledge	Belief	Confidence	Knowledge	Belief	Confidence	Knowledge	Belief
Camera on Tool	44,3	60,3	24,4	49,7	50,4	25,6	42,3	42,9	19,0	41,6	39,0	17,0	43,1	46,2	21,7
Sterio vision	80,6	68,2	55,8	64,4	57,1	37,3	34,7	42,9	16,3	60,7	52,9	32,4	61,4	52,5	33,6
TOF Camera	49,2	52,8	27,7	56,9	49,4	27,6	43,0	42,9	19,1	52,6	35,1	19,3	63,9	50,5	32,9
Structured light	45,8	50,6	23,9	51,7	41,7	22,2	43,6	42,9	19,4	56,3	44,8	26,9	44,4	31,6	14,1
Time of flight laser	56,0	55,7	28,9	58,5	49,5	30,0	62,3	63,4	40,7	68,1	55,0	38,4	62,7	52,1	34,3
Triangulation Laser	56,2	56,6	29,4	56,8	54,6	30,0	59,8	60,8	37,7	65,9	55,2	36,7	64,1	50,7	34,1
Projected IR light	74,9	39,5	29,3	72,6	44,5	33,9	80,0	48,9	39,1	73,2	55,3	40,5	46,5	26,6	12,5
Kinect	74,3	58,6	45,2	56,2	45,5	26,6	66,7	52,2	35,3	58,7	53,7	31,8	55,0	55,3	30,6
Visable Light com	75,8	59,0	46,3	70,2	45,8	32,9	63,8	59,9	38,2	71,5	60,2	43,6	45,9	23,1	10,8
ToF	80,4	60,4	49,4	72,4	46,6	34,1	71,3	45,9	32,6	79,8	80,4	64,8	59,6	50,9	30,4
Triangulation and AoA	79,1	60,4	48,7	62,9	38,7	26,3	72,5	43,5	31,3	75,0	76,4	57,8	61,1	46,1	28,3
TDoA	78,7	60,8	48,6	52,4	39,4	24,1	65,4	45,9	29,6	62,7	68,8	46,1	64,0	42,6	28,0
Ultrawideband	72,0	91,5	66,4	68,0	57,6	41,6	65,8	53,2	35,4	67,5	52,2	40,9	61,1	50,0	31,1
Artifical AC magnetic field	78,6	61,8	50,1	71,4	44,8	33,4	70,5	42,2	30,0	67,5	49,4	34,2	58,5	27,7	16,7
UWB, IMU & dead reckoning	56,7	68,1	33,4	50,1	50,4	25,8	68,2	47,5	33,3	57,6	48,5	27,9	63,8	40,9	26,5
Camera and laser	54,2	28,3	14,7	59,4	27,6	17,3	65,6	31,6	20,9	65,9	40,6	28,5	73,8	67,6	50,9
FARO	70,6	46,4	36,8	66,4	38,7	26,8	77,4	59,2	46,1	71,8	45,9	35,7	64,5	34,5	22,6
		Avg Belief	38,8		Avg Belief	29,1		Avg Belief	30,8		Avg Belief	36,6		Avg Belief	27,0

C Appendix

	Accuracy	Difficulty of manipulation of system	Update freq >10Hz	Pos lag of sys <200ms	Pos tool <500 mm accuracy in workspace	Cost	Robustness in industrial environment	6 dof positioning	size of system	weight	intrusiveness
Sum	**23,75**	**7,75**	**8,625**	**7,625**	**9**	**1,375**	**15**	**13,125**	**4,875**	**3,625**	**5,25**
Stefan	30	5	10	9	5	1	15	20	2	2	1
Elin	25	8	10	10	20	1	10	10	2	2	2
Satyajit	20	8	2	4	1	1	20	20	8	8	8
Linxuan	20	10	12,5	7,5	10	2,5	15	2,5	7,5	2,5	10
Mathias	30	8	15	14	5	2	11	7	1	2	5
Michael	25	5	3	5	5	7	21	22	3	3	1
Björn	20	3	10	15	10	5	15	15	3	3	1
Tobias	15	15	1	15	1	12	20	10	1	5	5
Adam	25	6	14	7	10	8	4	20	3	2	1
Christoffer	30	5	8	4	4	5	8	20	7	5	4