The Computer Aided Positioning System (CAPSY)

a low cost positioning system for construction

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1. INTRODUCTION

The level of automation and robotization in construction is very low. In particular in comparison with industrial activities. Ample reasons can be given for this. One of the technical reasons is the positioning problem of machines and tools. In an industrial activity machines and equipment are in a fixed position and the product is advanced towards the machine. In construction the machine has to move towards the product or even trough it. Moreover the product may have many shapes during the construction phase for it changes continuously. A system showing in one way or another its position in a continuously changing environment may provide an enormous support for construction machines and tools. However it should comply with a number of requirements to be useful in the construction industry.

- An accuracy of about 3 mm.

  This is an accuracy obtained in practice with traditional measuring methods. Somewhat higher accuracies are occasionally required, but that always within a very restricted area (2 to 3 meters) and with respect to an existing construction part. For another category it is even one order too accurate. Piles, work floors, sewage systems, sand plans etc. do not require more than a few centimetres of accuracy.

- Simple and immediately applicable.

  The system should be applicable without special operator and without drastic preparations. If the prospective user should first have to follow a course of a few days, it is not applicable. In that case a selective group of people is formed, capable of using it, and that detracts from its applicability. In addition it should be applicable without extensive preparations. This requires a carefully planned user interface, or possibly even a plurality of user interfaces. For instance the foreman of a finishing team for ceiling works may wish to have the drilling points presented in a graphic manner. In that way he doesn't have to work with data but receives the information in a suitable manner for him.

- Applicable within the conventional method

There are many sound and even necessary reasons to review the stages from design to construction drastically and to reorganize things according to more modern methods (computer supported). However it is impossible to equip only one facet on modern lines and to ignore that the remainder is still carried out in a conventional manner. If the positioning system would require a revolution in construction it is unsuitable. It should replace the existing manner of measuring and tracing, or should be capable of being replaced in turn by the existing method.

- Low cost

For making it to a piece of equipment in general use, the price is of decisive importance. The allowed order of magnitude is once or twice the price of a theodolite. This has fundamental consequences for the design. The applied technology should thus be inexpensive in manufacture and also inexpensive in application.

- Solid construction

The instrument should be resistant to weather and wind, dust and rough treatment. This makes a solid housing a necessity in avoiding damage. But this also affects the design inside the housing. It should be designed and manufactured in such a way, that a shock will not cause disorder. A disorder is difficult to detect and thus even more fatal than external damage.

2. TRIANGULATION

A number of methods are available to determine a position within a given area. In order to be able to select the proper method, attention should be paid in particular to two criteria: in the first place the accuracy, and in the second place its 'useability'. Thus the position can be determined with a measuring tape and/or theodolite. This will result in an accurate position, if performed properly. However the method is completely useless for practical considerations. The manual interference of a human being does not provide a positioning system for a computer controlled machine.

Another method would be to measure accurately the path covered. It is fairly simple to provide a wheel with a measuring system for measuring distance and direction, controlled by the computer. The major disadvantage is however that the measurement is disturbed if contact with the ground goes lost (slipping or tilting). Moreover a cumulative measuring error will occur which will grow too high after some reciprocating movements.

A more reliable method is *triangulation*. In this method three or more points of reference with known position are allocated in the working area. By measuring the angle from the standing point between these three or more reference points the position of the standing point can be determined by means of some calculation. To that end there are two requirements:

a- a proper measurement of angle or distance
b- a calculation of the position

It will be obvious that computer support is required for both conditions.

3. GONIOMETRY

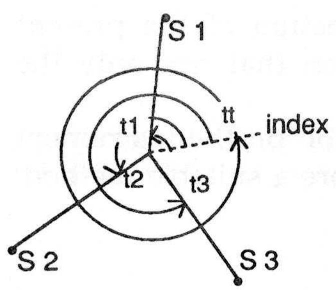
As stated, triangulation can be performed on the basis of the distances measured from the standing point to the points of reference or on the basis of the angle measured from the standing point between the points of reference. One way of determining the distance is the ultrasonic method. The time between transmitting a sound wave and receiving the pulse is a measure for the distance. However there are some problems. In the first place the velocity sound traveling through air is highly dependent on all kind of conditions (humidity, temperature, pressure). Errors can easily be several percents or the distance involved. A second objection of triangulation on the basis of the distances measured is, that it is not possible to determine the direction of the present position from such a measurement. We shall see later on that not only the position is of importance, but also the direction.

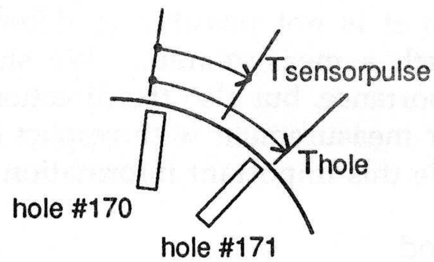
An angular measurement with respect to an orientation on the instrument itself does provide this important information and is therefore a suitable method.

4. CAPSY's method

The applied angular measurement by CAPSY is very simple in principle. A laser beam, rotating in a horizontal plane, hits a number of reference points during a rotation. The moment in time that a reference point has been hit with respect to the complete time of rotation is proportional with its angle within a total angle of 360 degrees (fig1). However this is only theoretical, for it assumes a constant speed of rotation of the laser beam. As the rotation of the laser beam is caused by a motor, a constant speed of rotation is wishful thinking. Even if this could be approached by a very special construction, the speed would be affected by every movement of the apparatus in such a way, that no correct angular measurement can be made. Moreover, one of the specifications (low cost) would then be at risk by the necessity of some special construction.

Designing CAPSY we did not make an attempt to approach the impossible, but applied the following philosophy: If the motor is not adapting to us, we will adapt to the motor! In other words: if the speed of rotation is not constant within one rotation, but it is known how the fluctuations are, then it will still be possible to carry out an accurate calculation. In order to map out the behaviour of a rotation properly, the rotation is subdivided into 1000 steps. This is done by mounting a disc with at its periphery 1000 holes on the rotating shaft of the motor. By registering the moment in time each hole passes, an accurate picture is obtained of the behaviour of each rotation. Theoretically every passage is a step of 360/1000=0.36 degrees. Unfortunately this is never accurate due to mechanical deviations. However it will be always the same! For every individual rotation! Considering the 1000 holes at their exact angle a table is obtained of hole passages with their exact angle. After every rotation a table is also obtained of 1000 holes with their exact time within the rotation. From here on it is fairly simple to measure the moment in time that a point of reference is hit by the laser beam and subsequently to interpolate to an angle between two calibrated passages (fig 2). In this way all fluctuations in the motor (whether caused by an irregular motor or by transverse acceleration) are eliminated. It has appeared from test measurements, that a stable angular measurement accurate to 0.001 degrees is possible. This meets the required accuracy as prescribed by the specifications. Moreover it meets also another requirement: simple solutions with respect to the price and the solidness of the apparatus. It does demand more from the computer support but that is exactly a category where the price/performance ratio is still improving dramatically from year to year. Moreover this provides considerable possibilities with respect to the production process to keep the apparatus low cost. This in contrast to the mechanical part of the equipment.





t1 : time from index to sensor # 1

t2 : time from index to sensor # 2

t3 : time from index to sensor # 3

tt : total revolution time

$$\angle H\ \text{sensorpulse} = \angle h\ 170\# + \frac{\text{Tsensorpulse} * (\angle h171 - \angle H170)}{\text{Thole}}$$

Fig. 1 (left) Angles S1-S3 are proportional with respect to total revolution time. Fig.2 (right) Exact angle by interpolation between holes

5. SENSORS/REFLECTORS

In the previous paragraph it has been described how CAPSY rotates the laser beam in a controlled manner. The laser beam will hit the points of reference during each rotation. The moments of hitting should be registered extremely accurately. For, as said before, that is decisive for the angle within the angle of rotation of 360 degrees. Moreover each point of reference should be distinguished in a unique way. For the calculation of the position the angle and the coordinates of the point of reference are required. By recognizing the points of reference individually it is possible to assign the proper co-ordinates thereto. In order to achieve this, the reference points can be made in two ways:

- active sensors
- passive sensors

An active sensor consists of a series of light-sensitive cells with electronics emitting a pulse when they are hit by the laser beam. This realization has a number of advantages, but also a greater number of disadvantages. The main advantage is the simple way wherein a pulse is generated and is passed to the computer. For all sensors are linked up to a cable and emit their unique pulse at the moment of the hit. The amplifying electronics encodes in this pulse the unique code and thus the signal can be registered by the CAPSY- computer in a simple manner.

However the disadvantages are obvious. Sensor boxes with electronics are awefull and require a troublesome cable between the sensors and the positioning system. This cable increases the vulnerability and limits the freedom of movement. These disadvantages makes the application of active sensors only of interest in a fixed arrangement (e.g. a gantry in a factory).

By designing the points of reference not as active electronics but as passive reflectors a wireless transfer of the signal can be obtained. Therefor the laser beam should be reflected by the reflector to be received in the positioning apparatus and transformed into a pulse. This way a cable can be avoided, for the pulse is now no longer made at the point of reference, but at the spot where the pulse is measured and processed as well. The principle of the angular measurement is not changed, but the technical performance is. With active sensors the light sensitive cells are hit by a hardly diverging laser beam. In the case of a reflected laser beam a considerable scattering does occur. This makes it necessary to collect the reflecting laser light with a (parabolic) mirror, and to concentrate it on a light sensitive cell. Reflectors are passive. No electronics are involved. This has as the advantage that they can be made inexpensive and simple. The disadvantage is the absence of the electronics which generate the unique pulse of each point of reference so that they can be recognized. This can be solved by executing the reflectors as bar codes. Thus every reflector may have its unique (bar) code and can thus be unraveled by the computer system as pulsating signal. Taking everything into account the advantages of reflectors are much higher than those of the active sensors. Reflectors are inexpensive, disposable, and do not require power and, above all, they are wireless.

6. CAPSY, the prototype.

In order to test the CAPSY-concept a first prototype has been built on the basis of active sensors. The purpose of this project was to test the computer-electronics, the method of angular measurement, and the positioning algorithm. Also an operational model is (notwithstanding its limitations) more convincing than a pure theoretical concept. At this very moment three prototypes are under construction on the basis of passive sensors (reflecting bar codes).

The CAPSY-system consists of three parts. The first part is the laser housing with the rotating mirror and the code-wheel. The second part is the computer with the interface for the processing of the signal. The last part is the sensor-box with sensors.

The laser housing comprises of a vertically positioned electro motor mounted on a shaft, and a code wheel and a mirror under an angle of 45 degrees. The solid state laser reflects the beam from above on the rotating mirror so that an imaginary horizontal plane is created. In this plane the sensors should be positioned. Exactly horizontal is not essential for the angle calculation. The solid state laser consists of a semi-conductor laser and a collimator. In addition the power supply for the laser and the decoder for the code-wheel are located at the laser housing. This very compact construction makes a hand held version possible (fig 3).

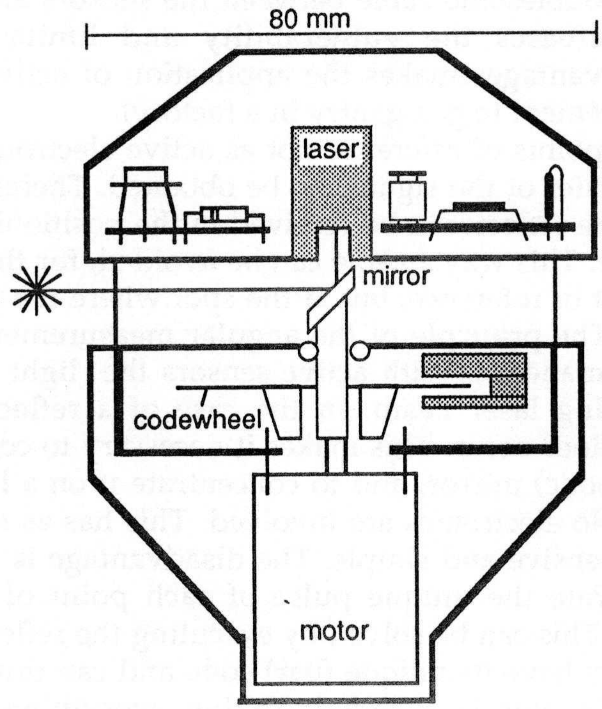


Fig. 3 Handheld laserhousing.

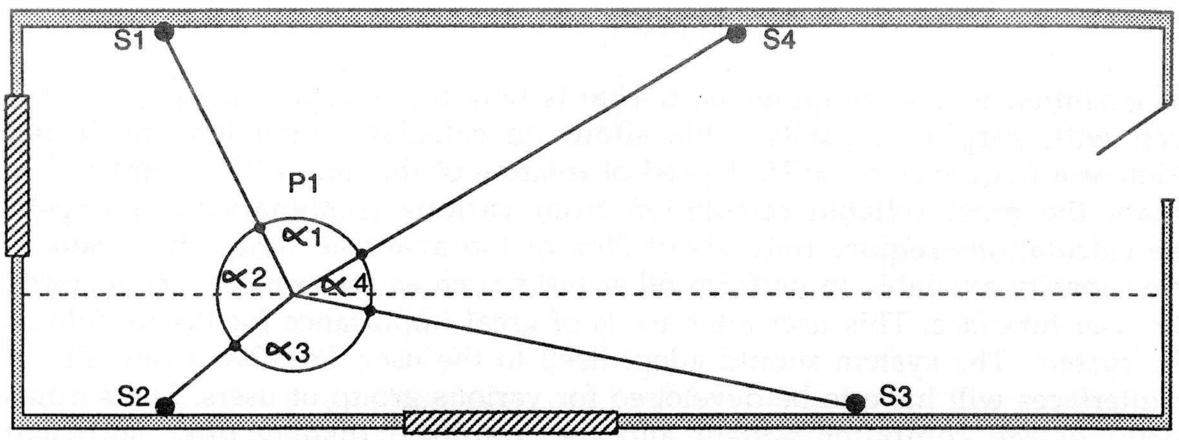
The laser housing is connected with the portable computer system by means of a small cable. The computer system consists of a Motorola MC68030/MC68882 microprocessor and 128Kb memory. The power supply is a 12 V loadable battery. The signal processing electronics are interfaced through a 32-bits wide fifo. The communication with the outer world takes place at two levels. A manual interface by means of a key-board and a graphic lcd- screen. A numeric interface can provide a machine with input by way of a serial/parallel gate.

The computer occupies a central position in the CAPSY-system. The philosophy is to use as few as possible mechanical components and external electronics. Moreover these components should be standard products. Calibrations, compensations etc. should take place in the software. Thereby the chief point is shifted to the computer part. That is why a powerful microprocessor is chosen with surplus capacity. This allows to calculate some ten angels per rotation at a frequency of 60 Hz (speed of rotation of the motor 3600 rpm) and to evaluate the most reliable calculation from various combinations of angels. These calculations require only about 20% of the available time. Thus there is ample capacity available to perform other tasks such as for example are required in the user-interface. This user-interface is of great importance for the usefulness of the system. The system should adept itself to the user. Possibly a plurality of user-interfaces will have to be developed for various group of users. The surplus capacity of the computer system and the graphical display offer sufficient possibilities to that end.

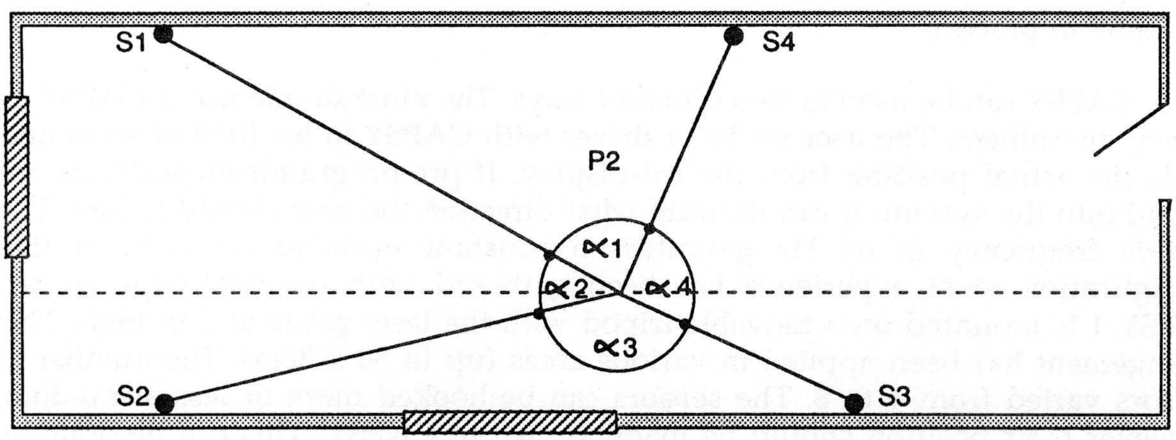
7. CAPSY in practice

CAPSY can be used in two different ways. The most simple use is CAPSY as survey instrument. The user walks or drives with CAPSY in his field of work and reads the actual position from the lcd-display. If pre-programmed positions are loaded into the system, it can indicate what direction the user should follow. The update frequency of 60 Hz garantees a constant updated read-off. In this configuration most experience has been gathered with the prototype so far. CAPSY-1 is mounted on a movable tripod with the laser plane at 2 m high. This arrangement has been applied in various areas (up to 30 x 30m). The number of sensors varied from 4 to 8. The sensors can be hooked more or less at random. However their position should be made known to CAPSY. This can be done by means of manual input of the xy-coordinates of each sensor. It may also be done by CAPSY itself. By measuring the angles of the sensors from two known points, CAPSY determines the coordinates of these sensors. After that CAPSY can be positioned everywhere in the working field to calculate his actual position (fig 4). The high stability and reproduceability of the determination of the position appeared from these test arrangements.

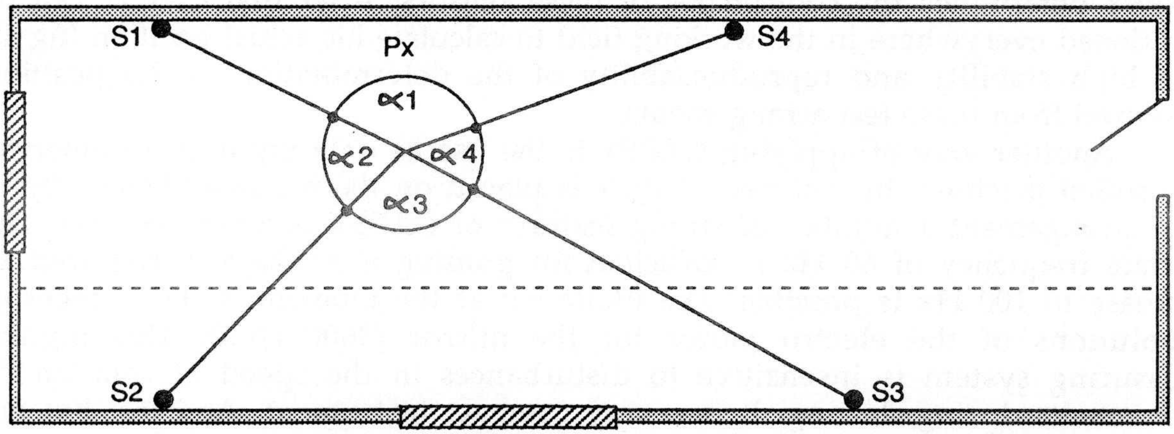
Another way of applying CAPSY is the use as data input of a numerical controlled machine. In that case CAPSY is placed on the machine. Especially in this arrangement a number of strong features of CAPSY become manifest. The update frequency of 60 Hz is sufficient for guiding a machine. If required an increase to 100 Hz is possible. The limitation at the moment is the number of revolutions of the electro motor for the mirror (3600 rpm). The angular measuring system is insensitive to disturbances in the speed of rotation by movements during driving. It is a very compact instrument. And last but not least: CAPSY has knowledge of its direction within the axial system. By knowing the mounting place on the machine and knowing its direction it is possible to calculate each point of the machine.



4a Step 1 : coördinates P1 are known, determine α 1 -α 4



4b Step 2 : coördinates P2 are known, determine α1- α4



4c Step 3 : determine α1 - α 4, calculate Position Px by triangulation with α 1-α 4 and the coördinates of S1 - S4.

Fig. 4 Calibration of the sensor positions

At this moment the following applications for CAPSY are in development:
- a handheld version for surveying
- a drilling robot for for ceilings and floors
- a machine for automatic drilling and placing of foundations for greenhouses
- a positioning system for a gantry
- a positioning system for AGV's in storehouses.

8. CAPSY's future

As CAPSY meets most of the requirements of the Construction Industry, many possible applications come forward. One particular interesting field of applications will be the combination of CAPSY with a productmodel of a construction. A productmodel is a computer processable information model, that describes the three dimensional reality of an object. Research in this direction will eventually lead to a new generation of computer aided assembly methods, both simple and sophisticated. An example of a rather simple example is a moveble device that can mount ceiling plates.

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