Sensors and Measurement Techniques for Position Recovery and Object Localization

Emil M. Petriu, Dr. Eng., FIEEE
Professor
School of Information Technology and Engineering
University of Ottawa
Ottawa, ON., K1N 6N5 Canada
petriu@site.uottawa.ca

Position Sensors - classified according to their range

1. **contact sensors**
    * make/break contact
    * tactile probes
    * analog position sensors
    * position encoders

2. **“near to”, or proximity, sensors**
    * close range sensors:
        - time-of flight (sonar, IR, radar)
        - triangulation
    * imaging
        - laser scanners
        - vision

3. **“far away” sensors**
    * long range sensors:
        - time-of flight (sonar, IR, radar)
        - triangulation
    * imaging
        - vision
        - radar
        - IR

The most common position transducers are: potentiometers, synchros and resolvers, encoders, RVDT (rotary variable differential transformer) and INDUCTOSYN.

Encoders are digital position transducers which are the most convenient for computer interfacing.

Incremental encoders are relative-position transducers which generate a number of pulses proportional with the traveled rotation angle. They are less expensive and offer a higher resolution than the absolute encoders. As a disadvantage, incremental encoders have to be initialized by moving them in a reference (“zero”) position when power is restored after an outage.

Absolute encoders are attractive for joint control applications because their position is recovered immediately and they do not accumulate errors as incremental encoders may do. Absolute encoders have a distinct n-bit code (natural binary, Gray, BCD) marked on each quantization interval of a rotating scale. The absolute position is recovered by reading the specific code written on the quantization interval currently facing the reference marker.

The metrological performance of a position recovery system three parameters: **accuracy**, **repeatability**, and **resolution**.

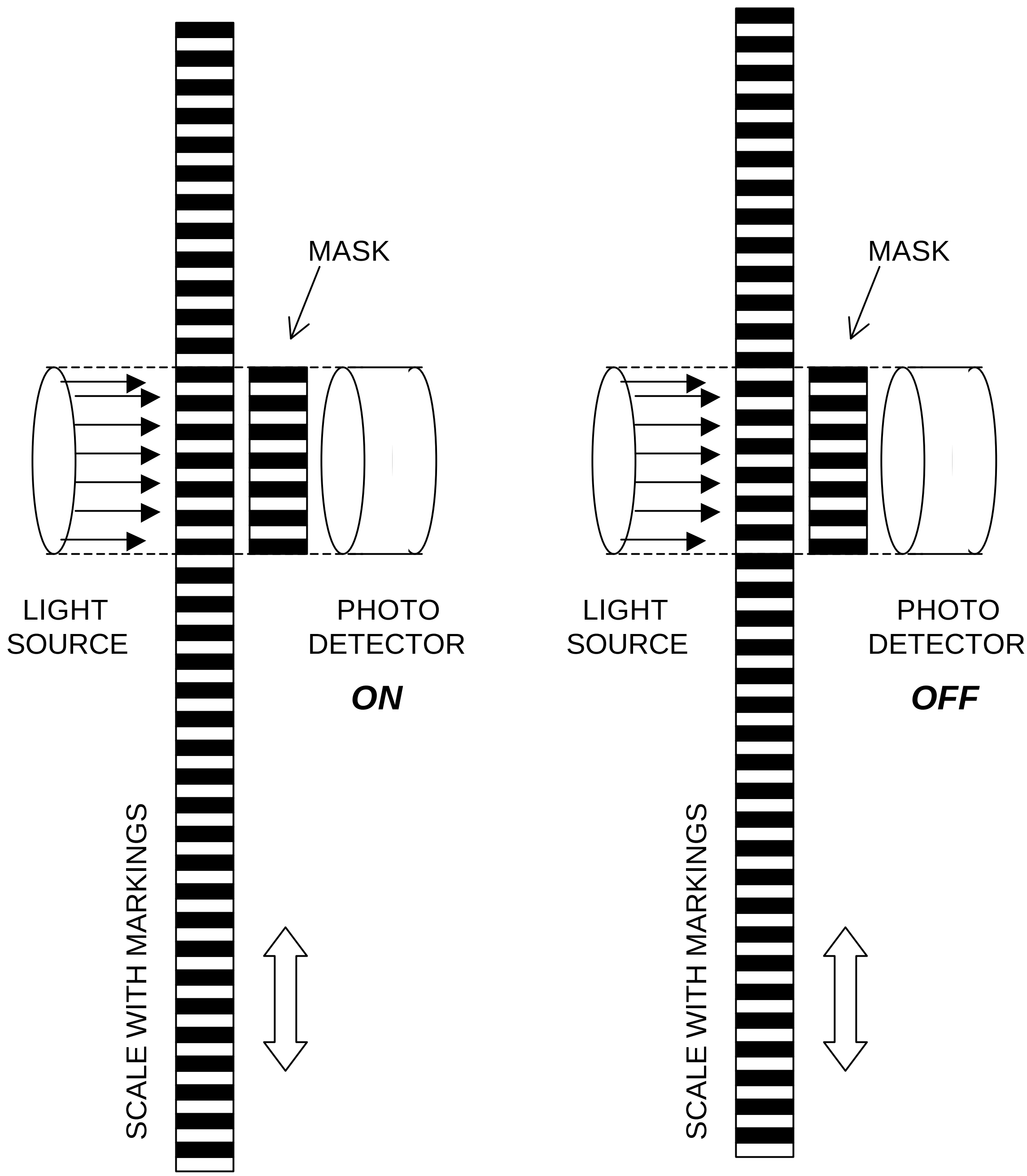
Accuracy is the difference between the actual location and the recovered location.

Repeatability is the variation in the recovered location.

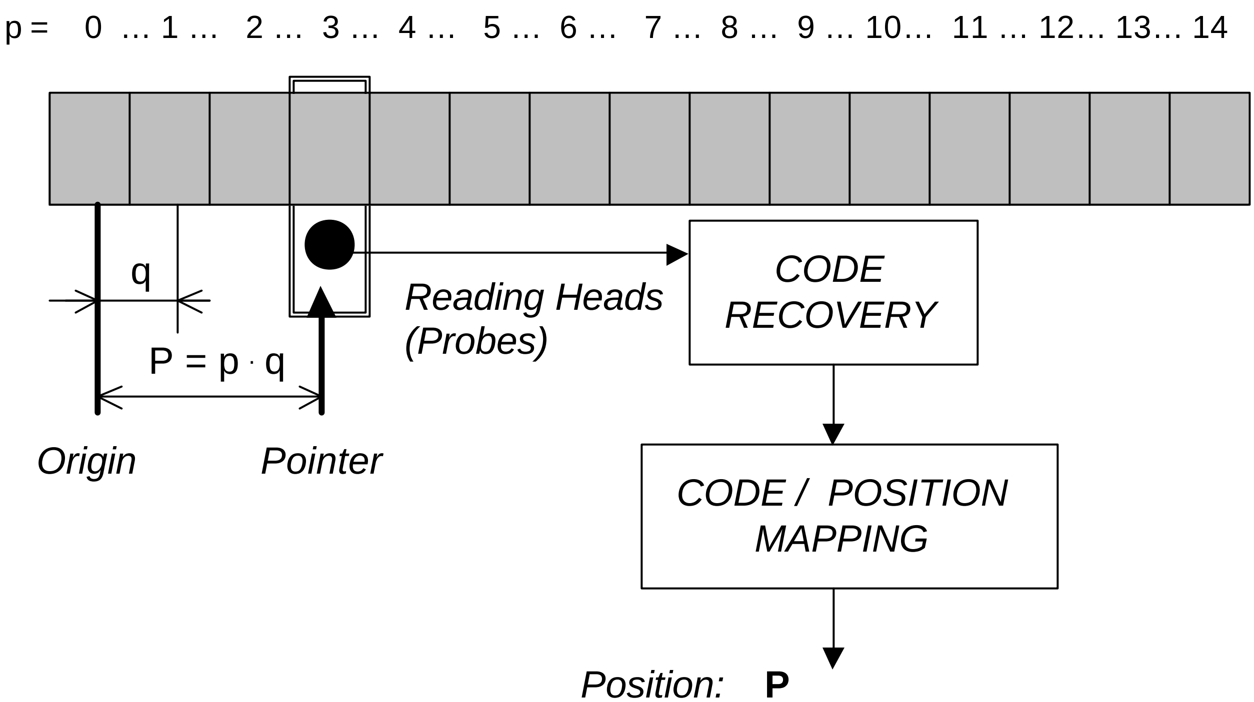
Resolution is the minimum distance that the measurement system can detect.

The repeatability and resolution of most system is better than their accuracy.

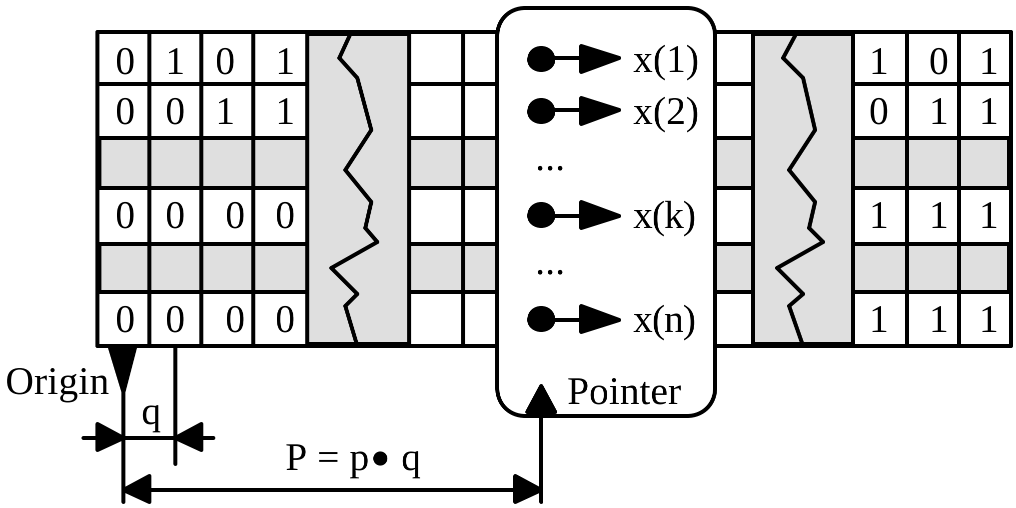
INCREMENTAL OPTICAL ENCODERS



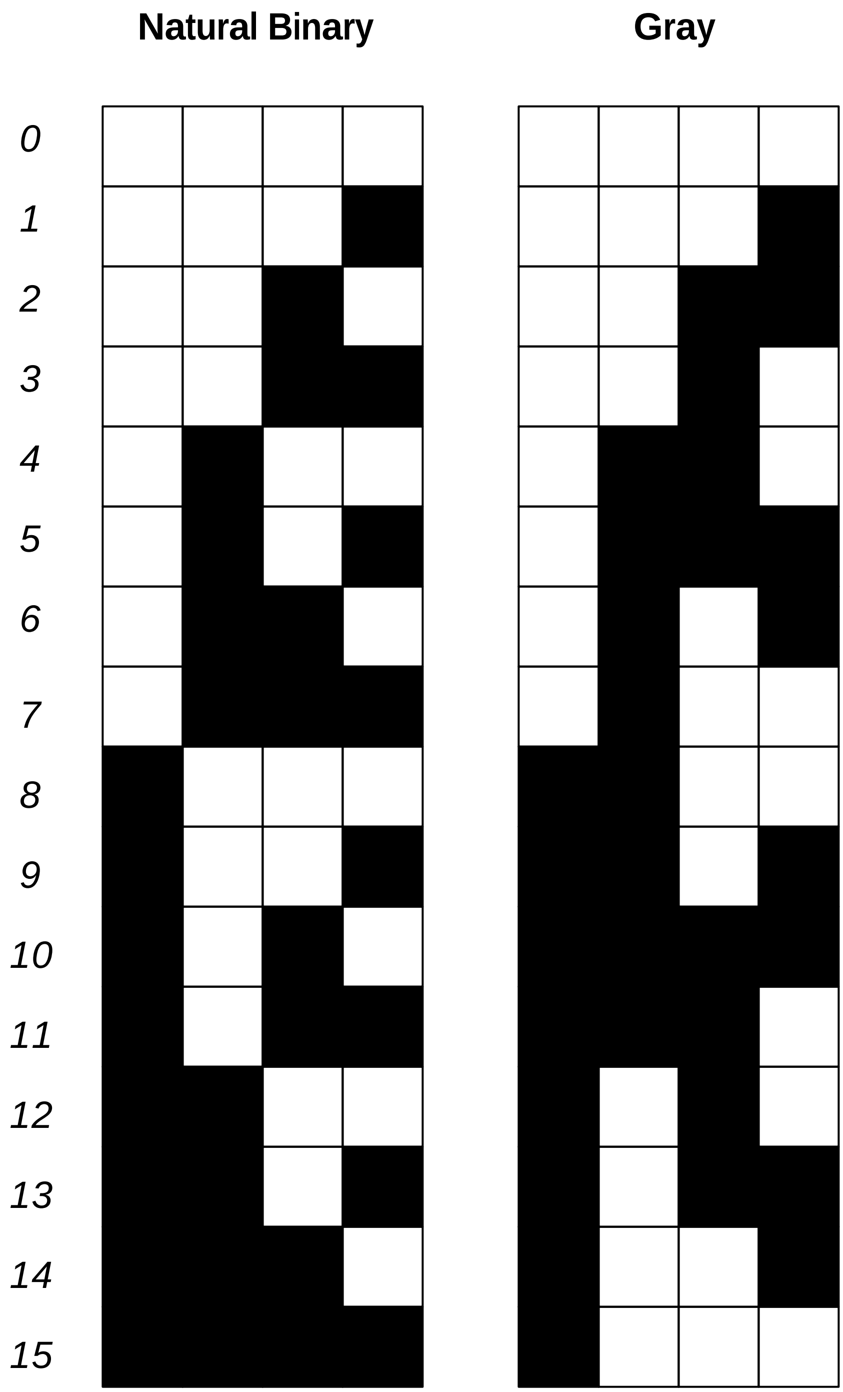
ABSOLUTE POSITION ENCODERS



The quantization intervals on the encoded track are conveniently marked in such a way that the code read for each quantization interval is unique being able to unequivocally identify each Interval. An a priori defined "Code/Position" mapping (mathematical function, or look-up table) is then used to recover the actual position of the quantization interval currently probed .
The most popular codes and associate probe (reading head) technology are binary. However there are now new computer vision, radio beacon, etc. probing technologies that allow multi-valued (polyvalent) marking of the encoded track.



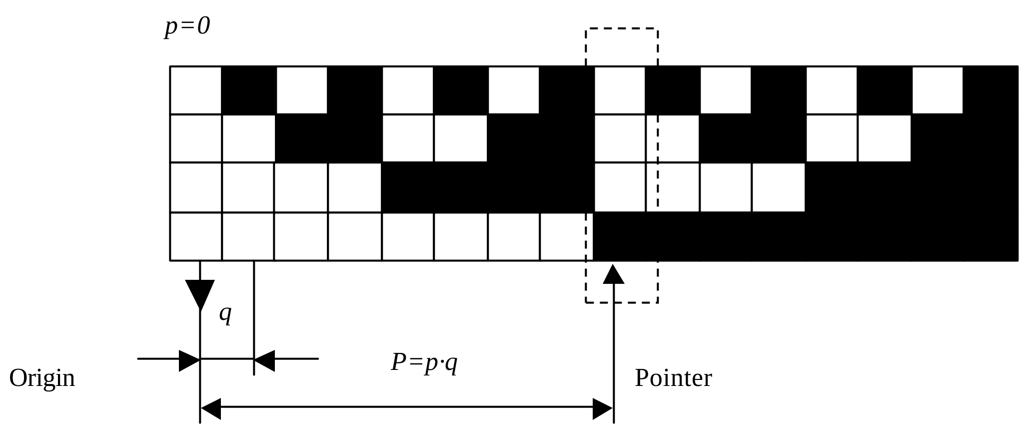
The straightforward approach for the absolute position encoding requires that each quantization interval of a scale be marked with a distinct n-bit code.


Natural Binary
Gray
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

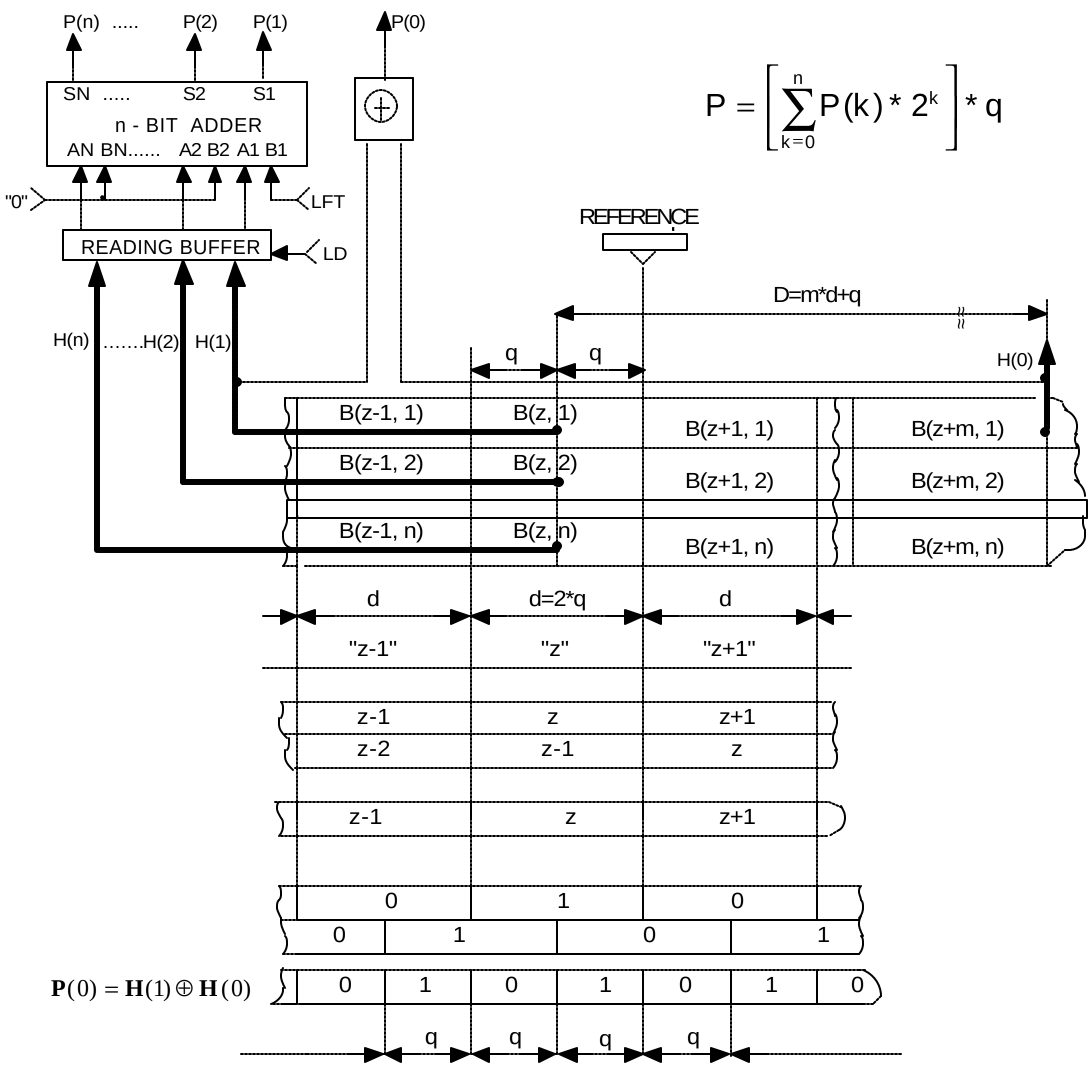
Absolute Natural Binary Encoder.

The position *P* of the pointer with respect to the origin of this scale is estimated by reading the specific code *{x(k)*? {0,1} */ k*=1,…,4*}* written on the quantization interval currently facing the pointer:

$$P = p \cdot q = \left(\sum_{k=1}^{4} x(k) \cdot 2^{k-1}\right) \cdot q \quad / \quad x(k) \in \{0,1\}$$



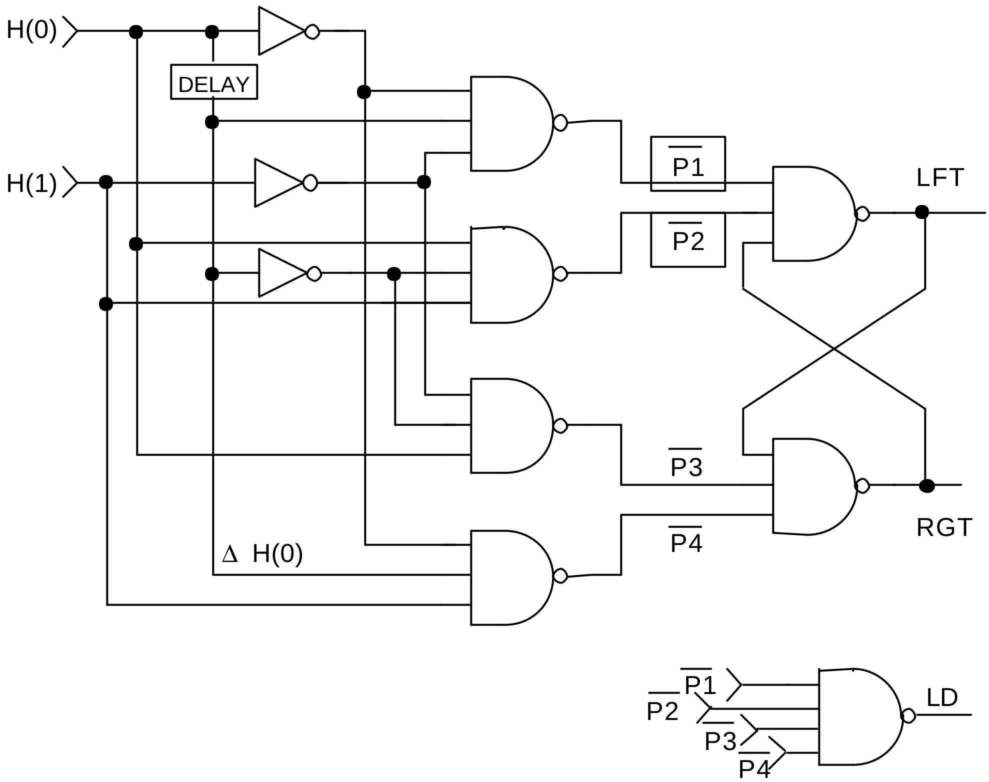
Absolute position encoding using a natural 4-bit code



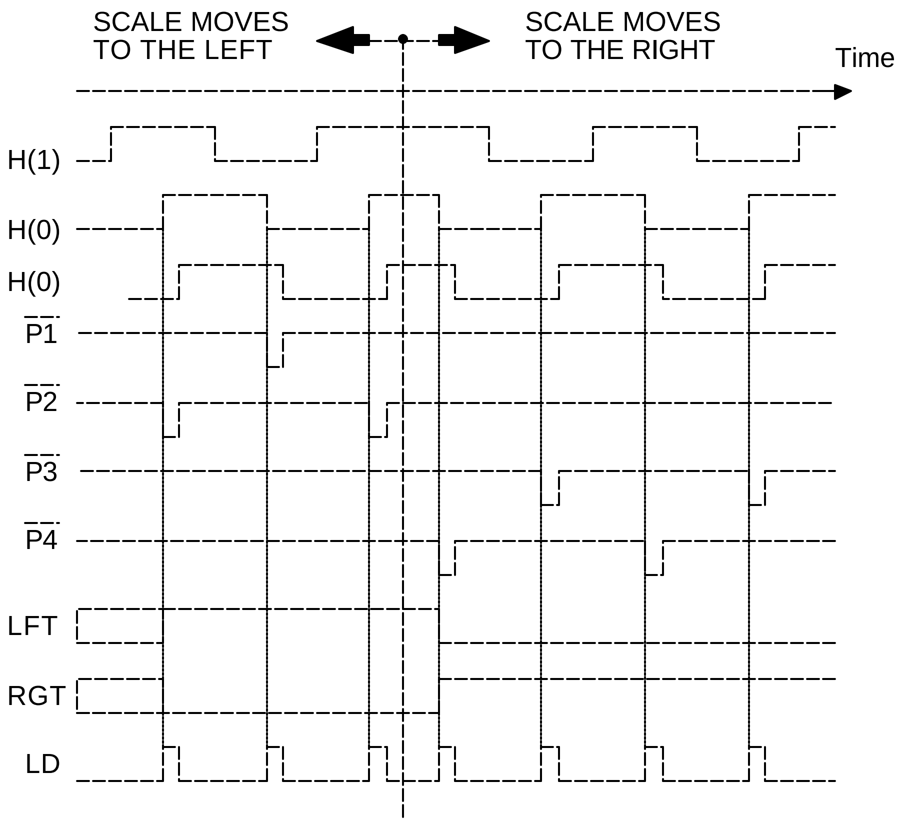
$$P = \left[\sum_{k=0}^{n} P(k) * 2^k \right] * q$$

$$\mathbf{P}(0) = \mathbf{H}(1) \oplus \mathbf{H}(0)$$

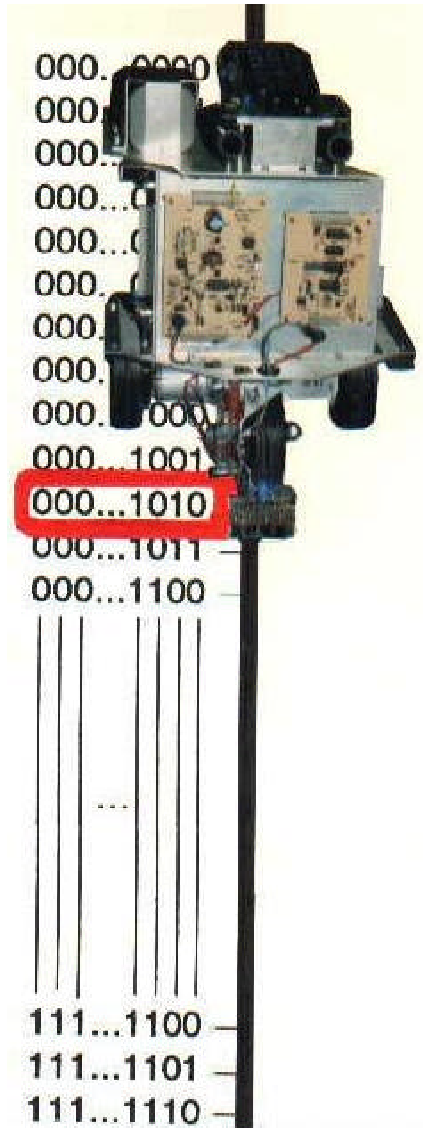
The (n+1) bit natural binary absolute encoder. A total of n+1reading heads are used, but only a number of n code tracks (the most significant) have to be physically implemented on the moving scale.



Code reading synchronization logic
for the natural binary absolute encoder



Time diagrams for the code reading synchronization logic



Why natural binary coding cannot be used in practice for absolute position recovery ?

A n-bit code would be needed for each quantization step, resulting in *n* binary tracks in parallel with the guide-path. For instance, the encoding of a 160 m long guide-path with a 0.01 m resolution would need 14 tracks running in parallel with the guide path

Pseudo-Random Encoding

A practical solution allowing absolute position recovery with any desired n-bit resolution while employing only one binary track, regardless of the value of n.

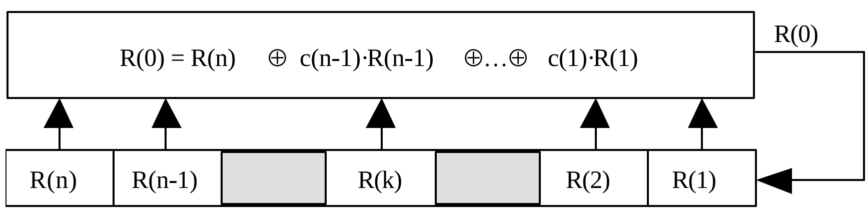
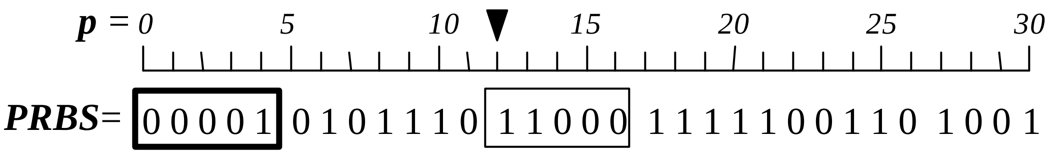


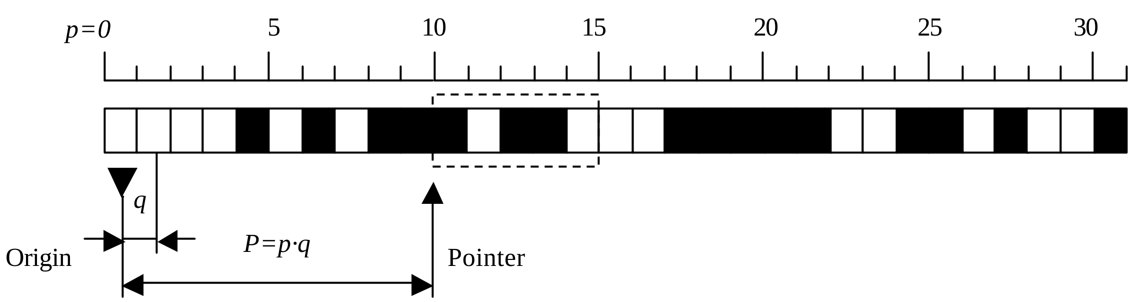
Table 1 Feedback equations for PRBS generation

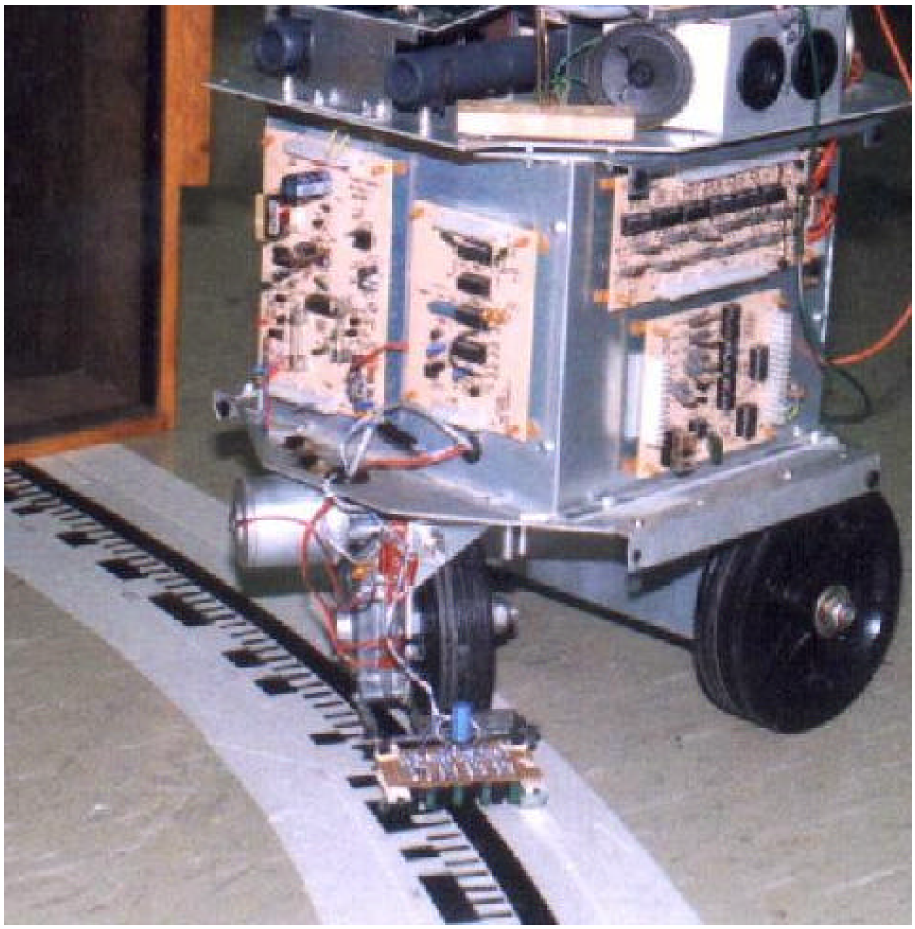
Shift register length *n*	Feedback for direct PRBS R(0)= R(n) ⊕ c(n-1)·R(n-1) ⊕…⊕ c(1)·R(1)	Feedback for reverse PRBS R(n+1)= R(1) ⊕ b(2)·R(2) ⊕…⊕ b(n)·R(n)
4	R(0) = R(4) ⊕ R(1)	R(5) = R(1) ⊕ R(2)
5	R(0) = R(5) ⊕ R(2)	R(6) = R(1) ⊕ R(3)
6	R(0) = R(6) ⊕ R(1)	R(7) = R(1) ⊕ R(2)
7	R(0) = R(7) ⊕ R(3)	R(8) = R(1) ⊕ R(4)
8	R(0) = R(8) ⊕ R(4) ⊕ R(3) ⊕ R(2)	R(9) = R(1) ⊕ R(3) ⊕ R(4) ⊕ R(5)
9	R(0) = R(9) ⊕ R(4)	R(10) = R(1) ⊕ R(5)
10	R(0) = R(10) ⊕ R(3)	R(11) = R(1) ⊕ R(4)



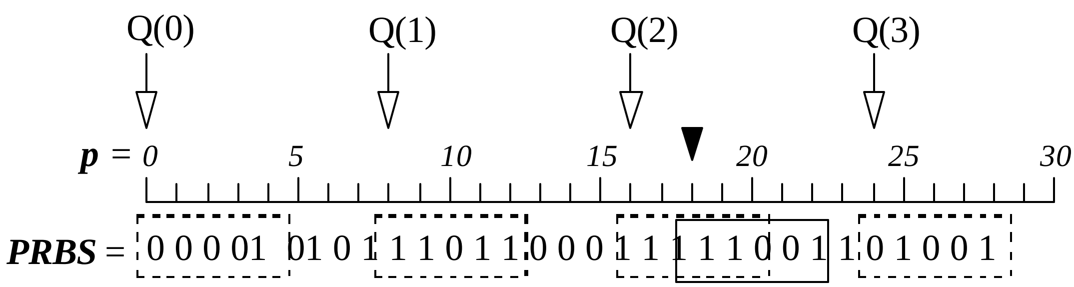
A (2^n-1) term Pseudo-Random Binary Sequences (PRBS) generated by a *n*-bit modulo-2 feedback shift register is used as an *one-bit / quantization-step* absolute code. The absolute position identification is based on the PRBS window property. According to this any *n*-tuple seen through a *n*-bit window sliding over PRBS is unique and henceforth it fully identifies each position of the window.

The figure shows, as an example, a 31-bit term PRBS: 0, 0, 0, 0, 1, 0, 1, 0, 1, 1, 1, 0, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 0, 0, 1, 1, 0,1, 0, 0, 1, generated by a 5-bit shift register. The 5-bit n-tuples seen through a window sliding over this PRBs are unique and represent a 1-bit wide absolute position code.

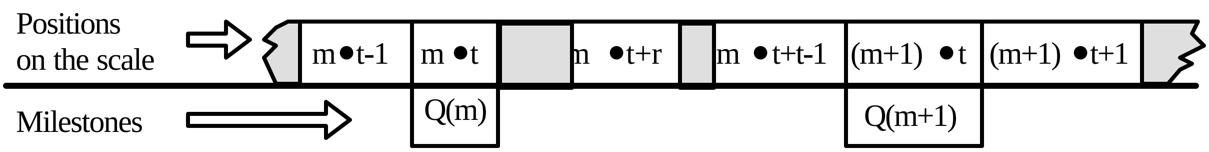


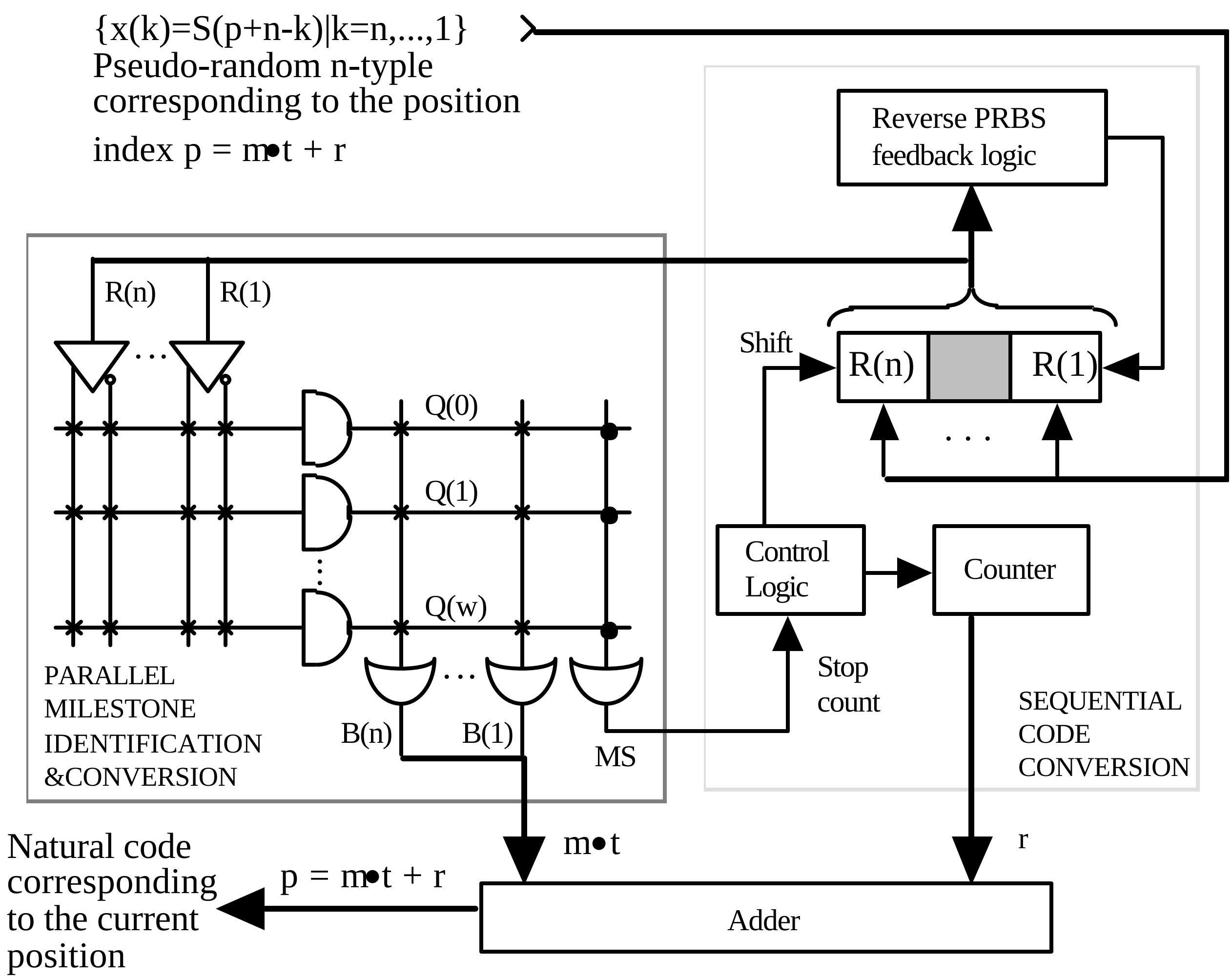


Pseudo-Random Binary Sequence (PRBS) encoded track with one bit per quantization step allows recovery of the absolute position of an optically guided Automated Guided Vehicle (AGV)

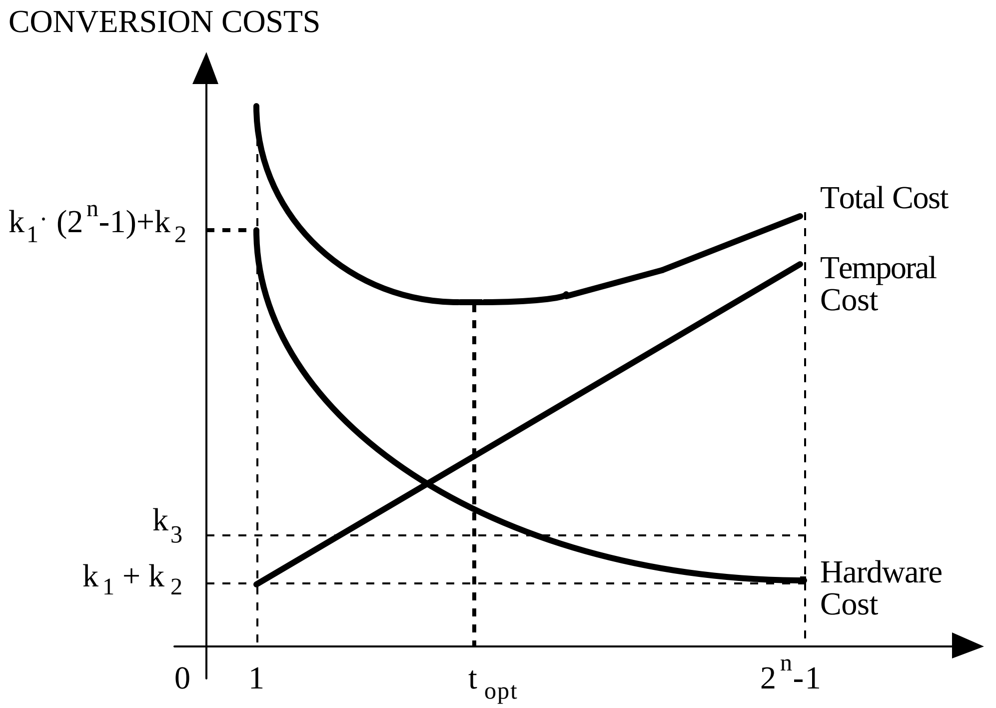


Serial-parallel code conversion of the absolute position p=18 on a 31-position PRBS encoded track with four milestones.

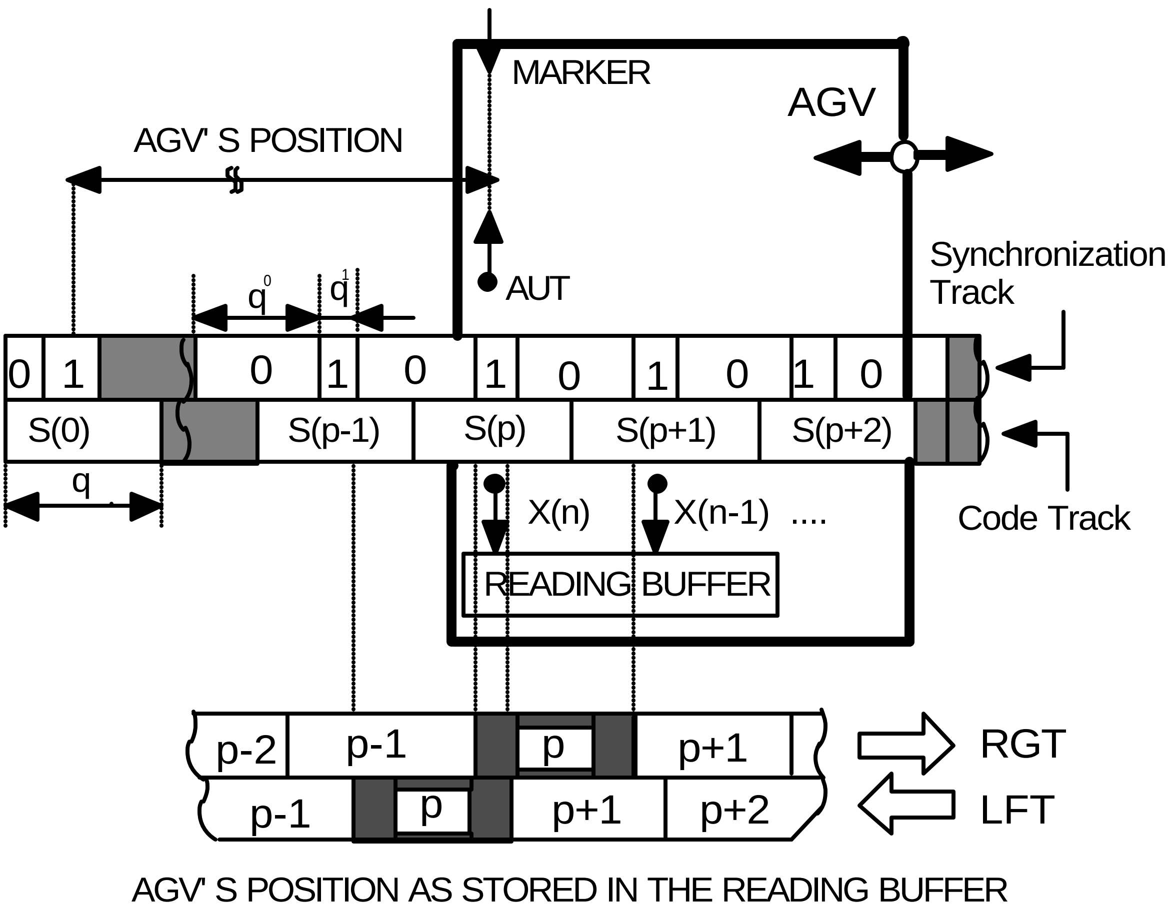




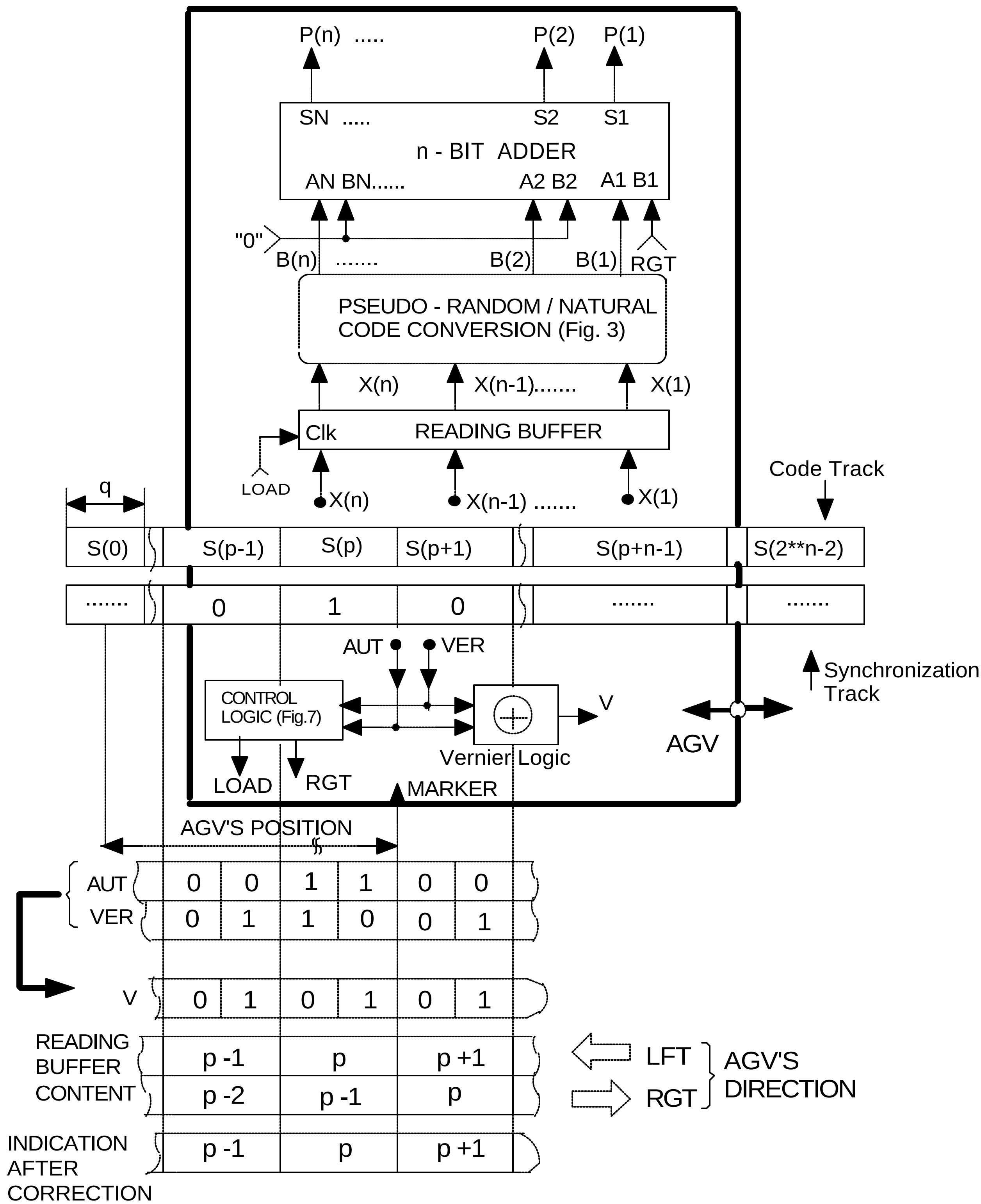
Serial-parallel pseudo-random / natural code conversion algorithm



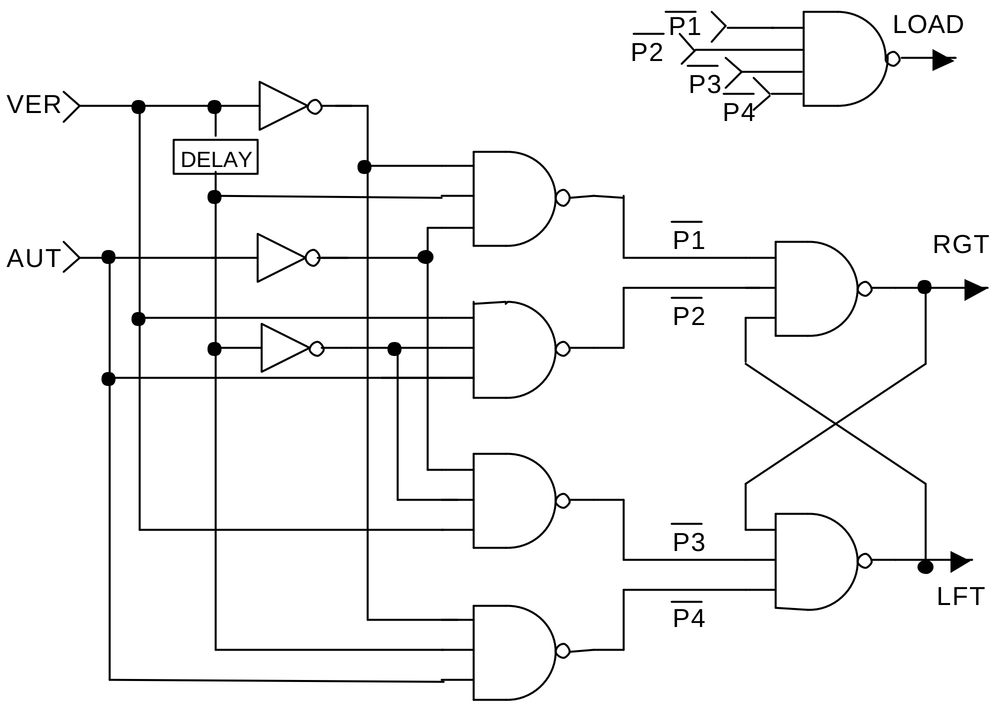
Serial-parallel code conversion costs as a function of the distance t between milestones. k1 is the equipment cost associated with each milestone, k2 is the basal hardware cost for the serial back-shift operations, k3 is the basal temporal cost for a fully parallel solution, and k4 is the temporal cost associated with each back-shift operation.



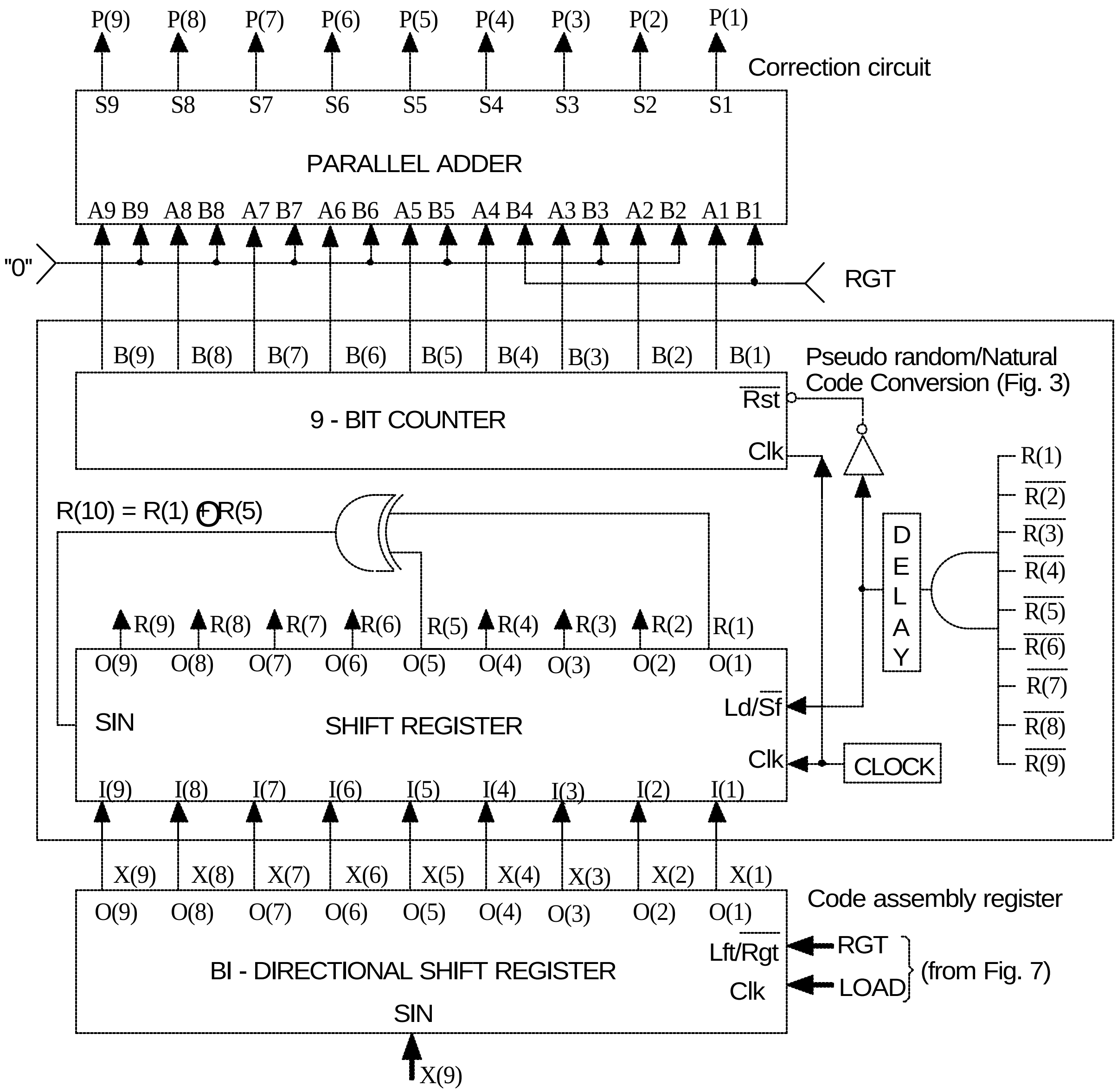
The "naïve" straightforward synchronization of the code readings introduces an "hysteresis error".



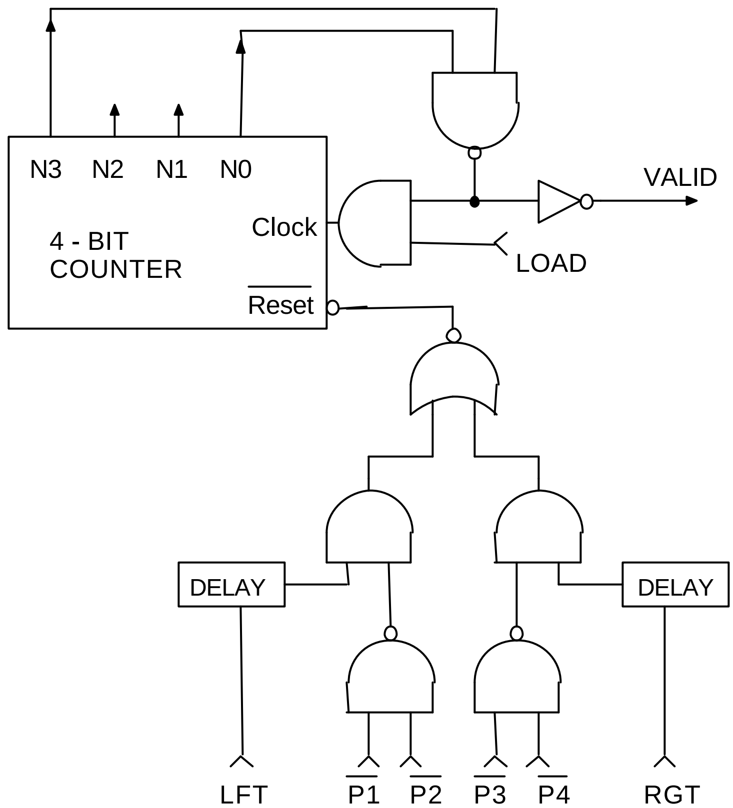
A more effective synchronization method which eliminates the “hysteresis error” and doubles the overall measuring resolution.



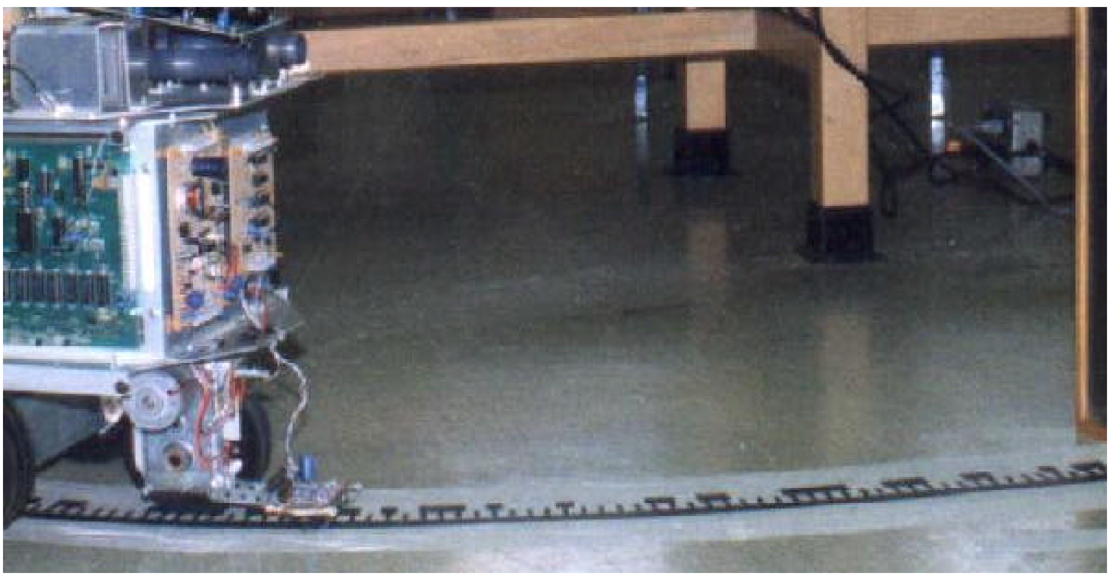
Synchronization logic



Implementation details of the PRBS
encoded absolute position measurement

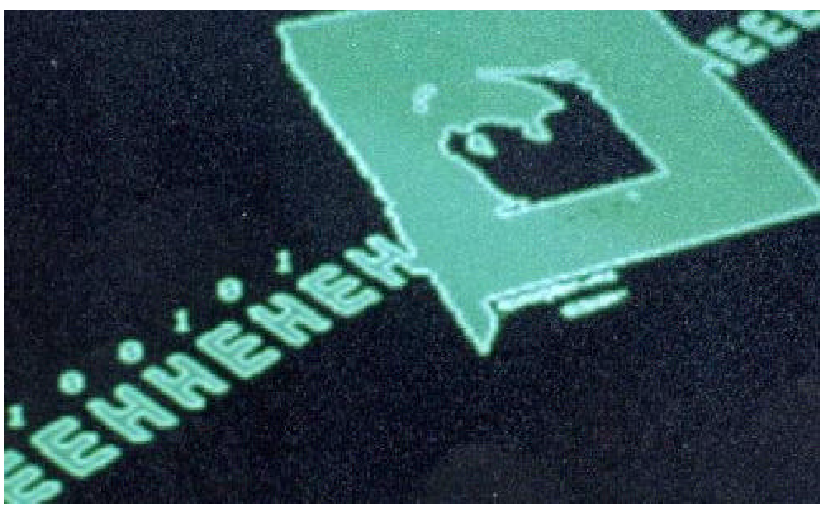


Protection circuit against measuring errors that occur when the AGV changes its moving direction on the guide-path.



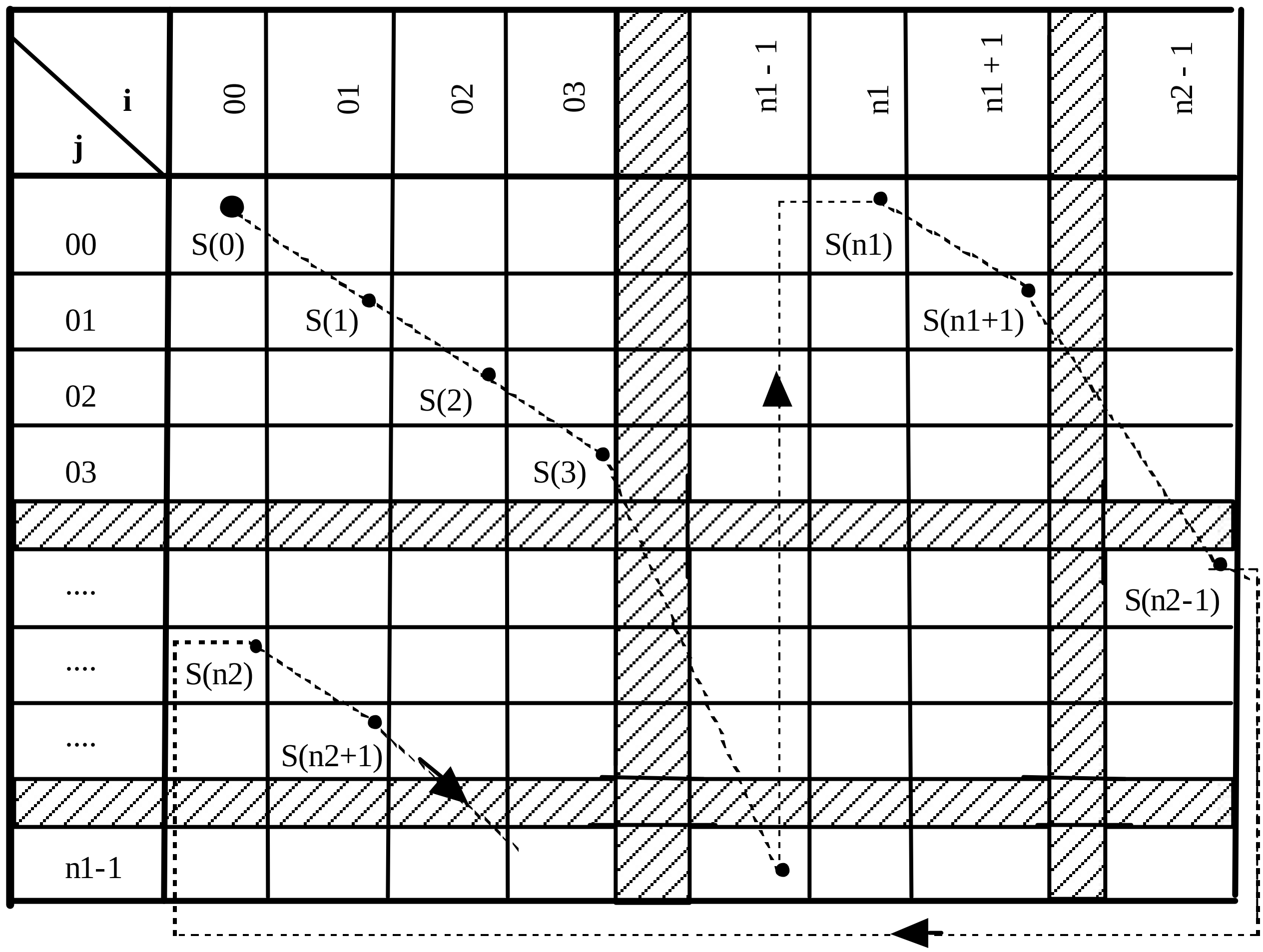
Optically guided AGV tracking a PRBS encoded guide path

PRBS encoded guide path allows recovery of the absolute position of an AGV using computer vision

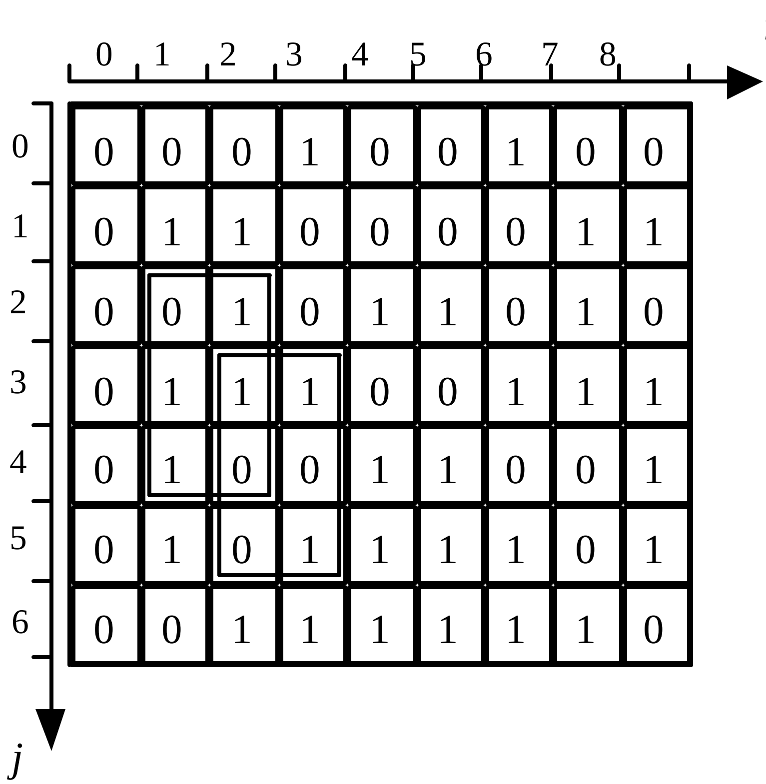


Computer vision recognition of the pseudo-random binary code

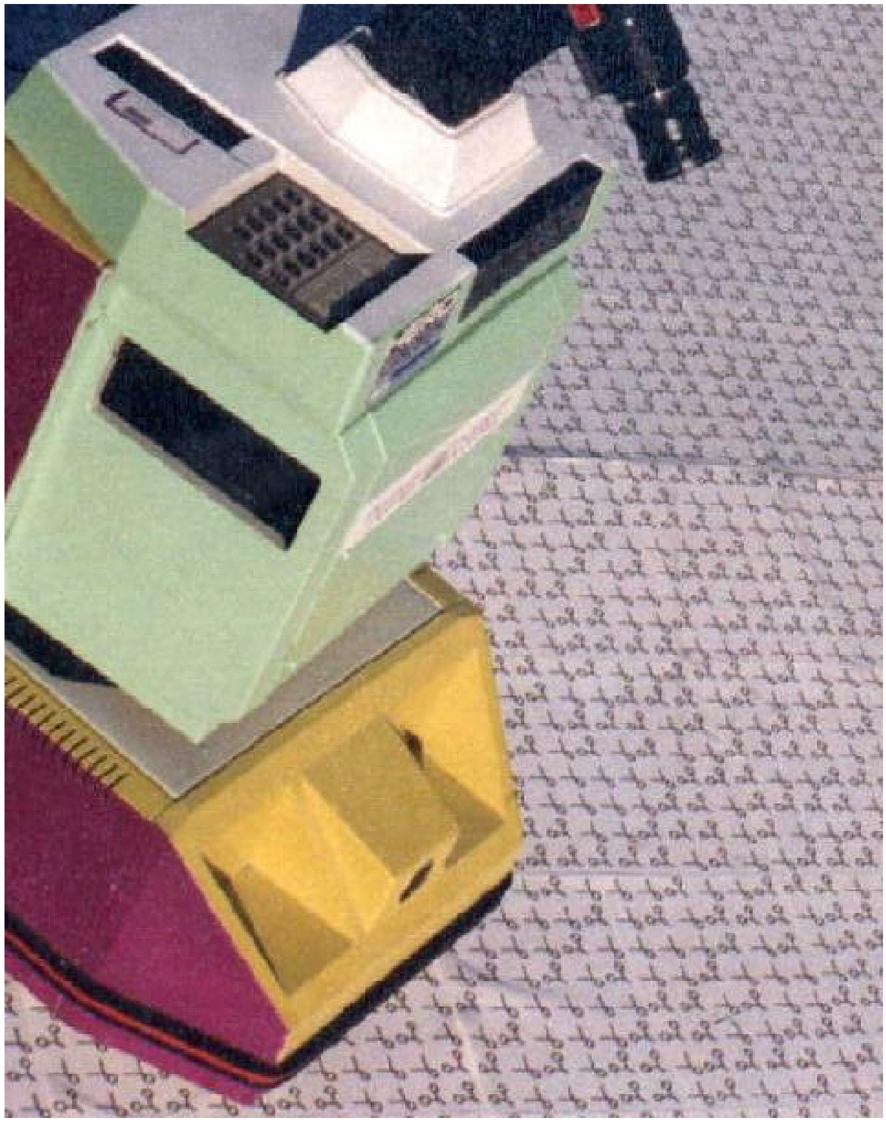
Wall-mounted PRBS encoded guide path allows recovery of the absolute position of the AGV using computer vision



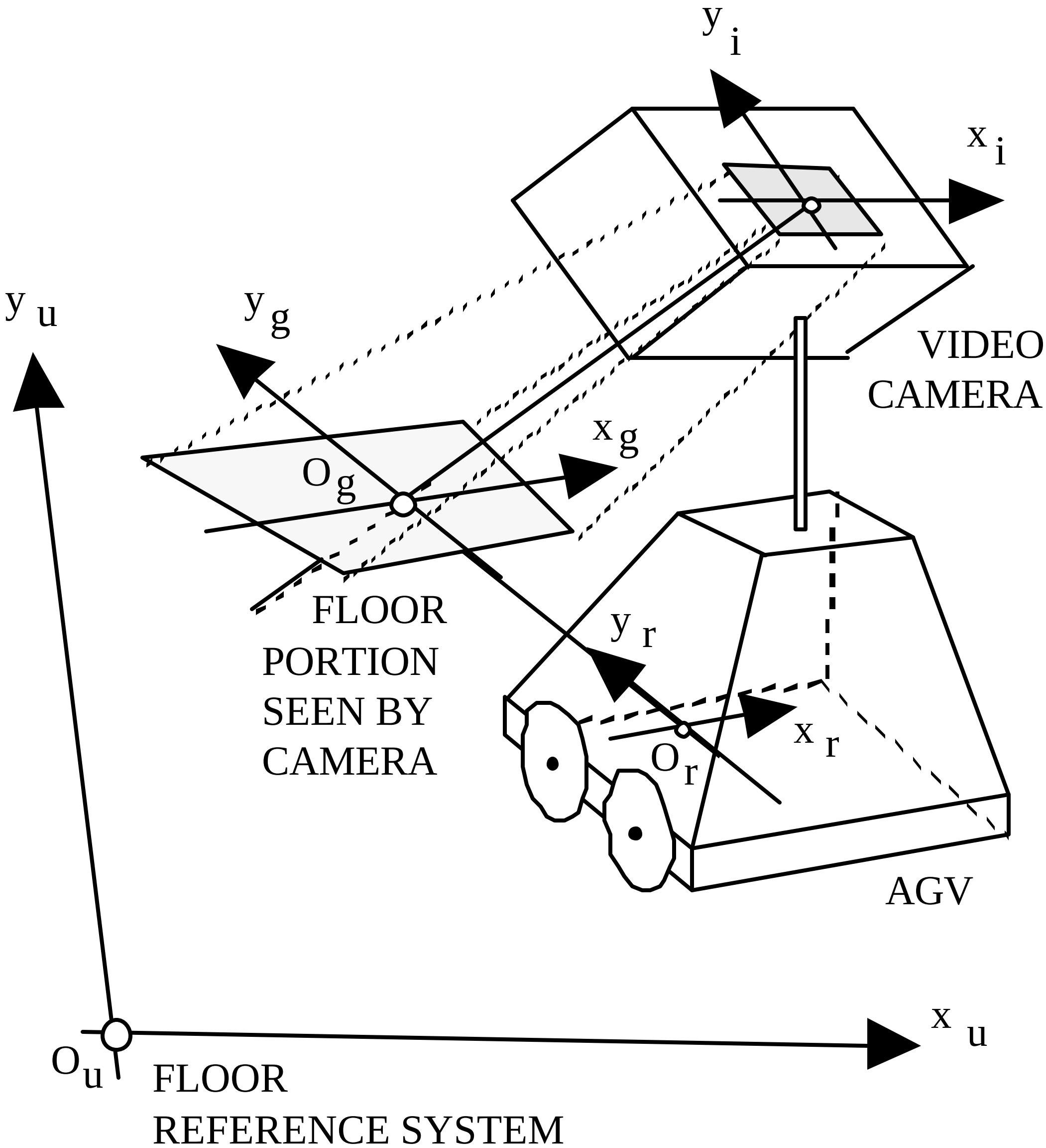
Folding a Pseudo-Random Binary Sequence (PRBS) to produce a Pseudo-Random Binary Array (PRBA)



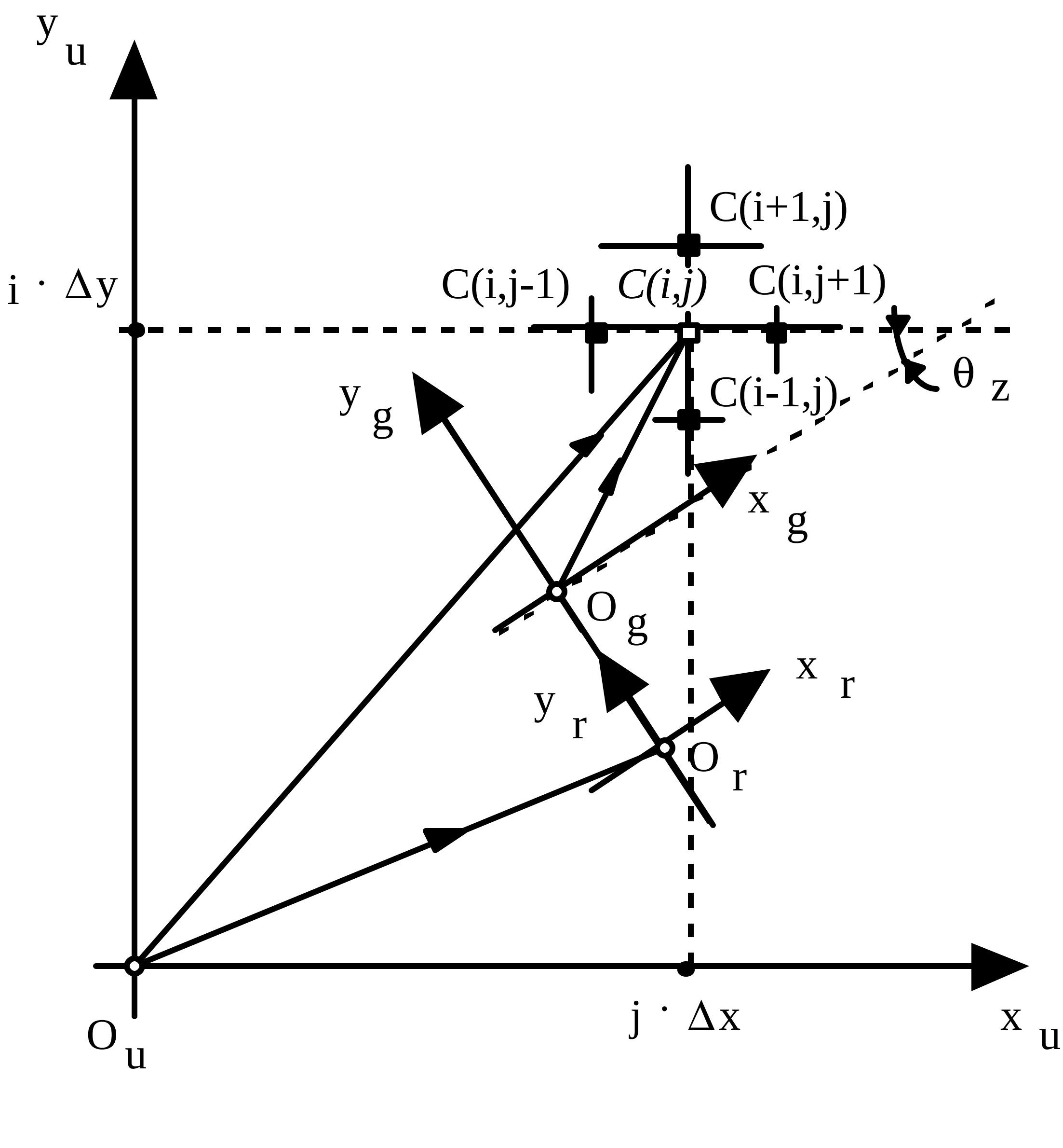
Illustrating the window property in a Pseudo-Random Binary Array (PRBA). The 3-by-2 code seen trough a window on a 7-by-9 PRBA is unique and used as absolute code for the window position (i,j).



Pseudo-Random Binary Array (PRBA) encoding for the recovery of the 2D absolute position of a free ranging mobile robot using computer vision

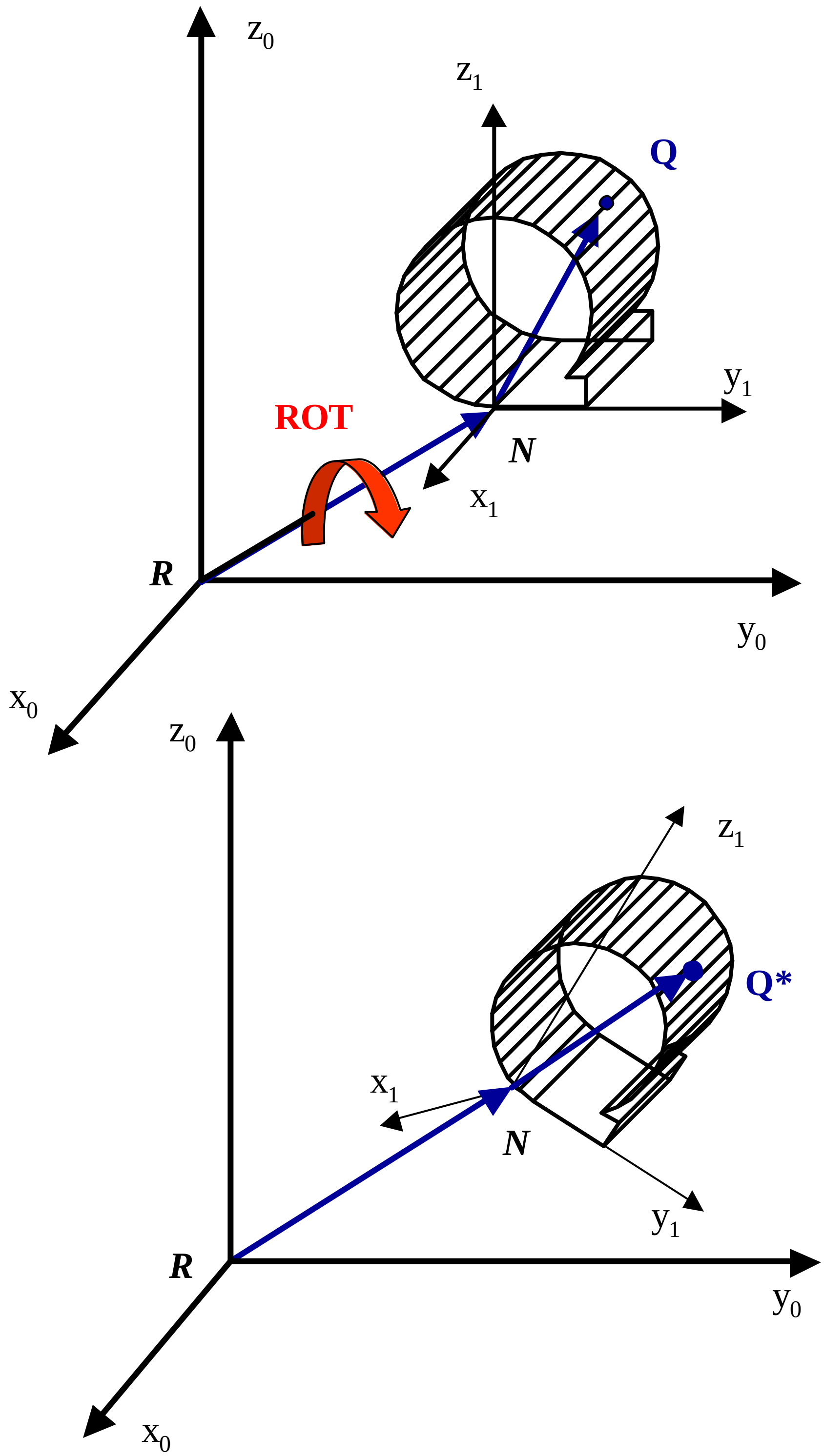


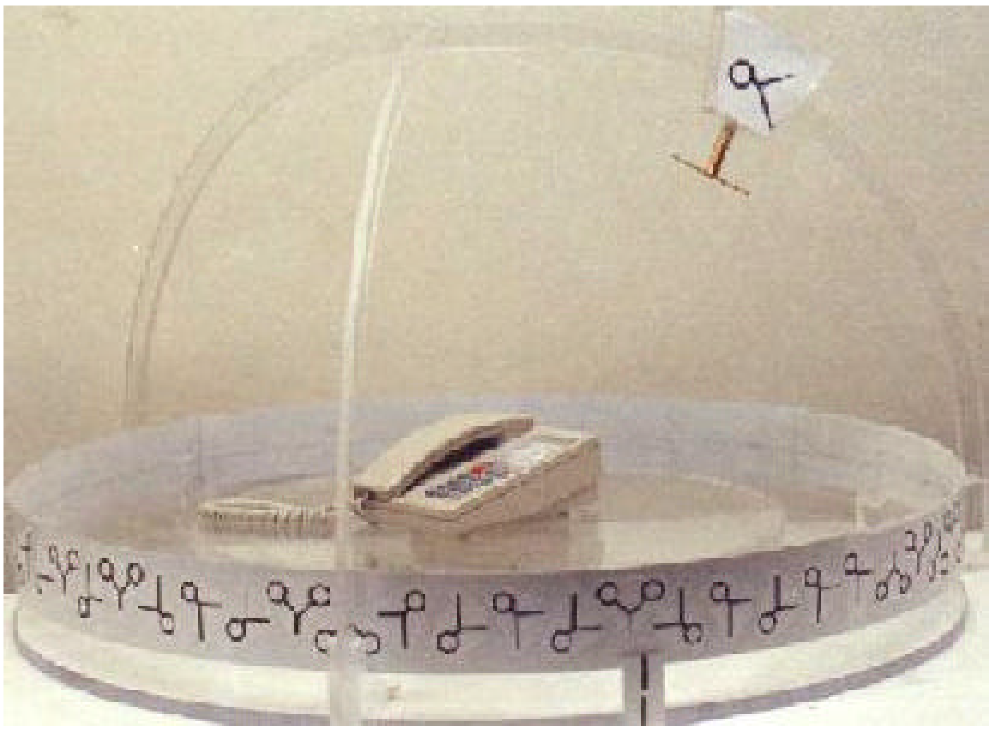
y_i
x_i
y_u
y_g
VIDEO
CAMERA
x_g
O_g
FLOOR
PORTION
SEEN BY
CAMERA
y_r
x_r
O_r
AGV
x_u
O_u
FLOOR
REFERENCE SYSTEM



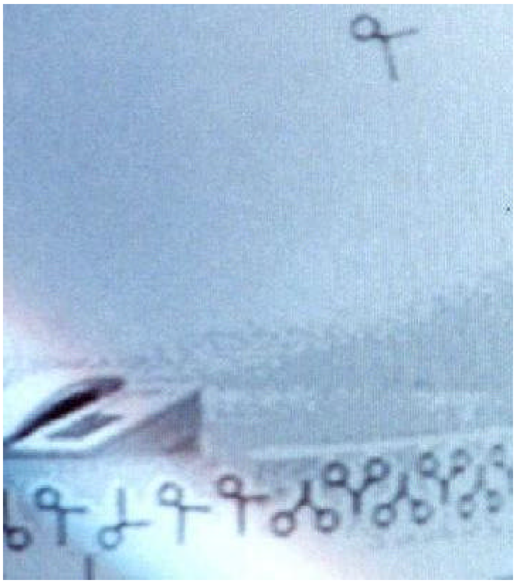
y_u
$i \cdot \Delta y$
C(i+1,j)
C(i,j-1)
C(i,j)
C(i,j+1)
θ_z
y_g
C(i-1,j)
x_g
O_g
x_r
y_r
O_r
O_u
$j \cdot \Delta x$
x_u

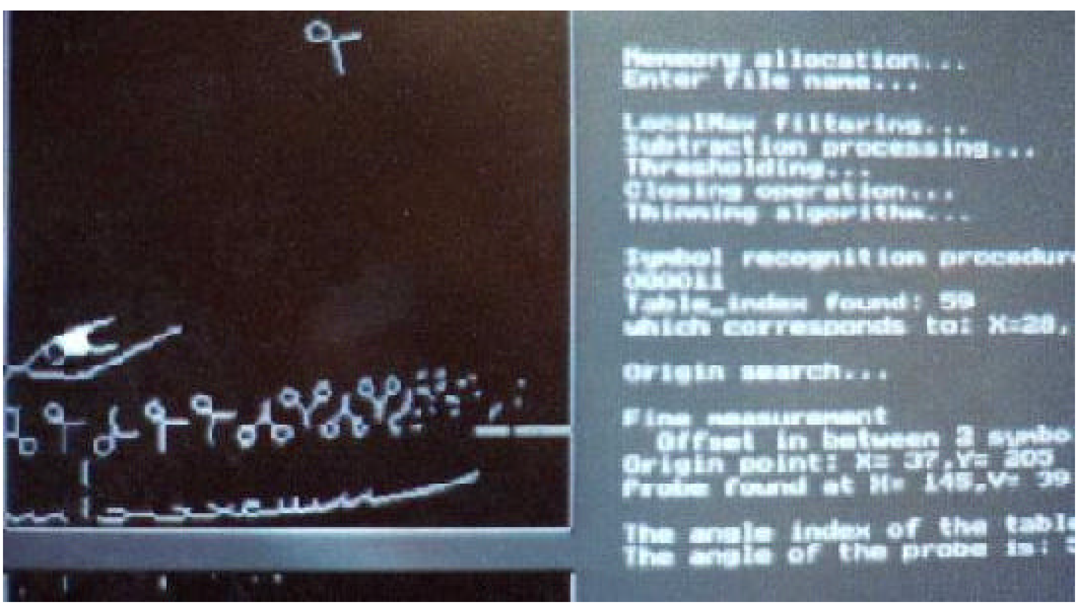
Recovering the Position and Orientation of 3D Objects





PRBS encoding for computer vision recovery of the 3D position of a probe mapping the electromagnetic–field radiated by a telephone set

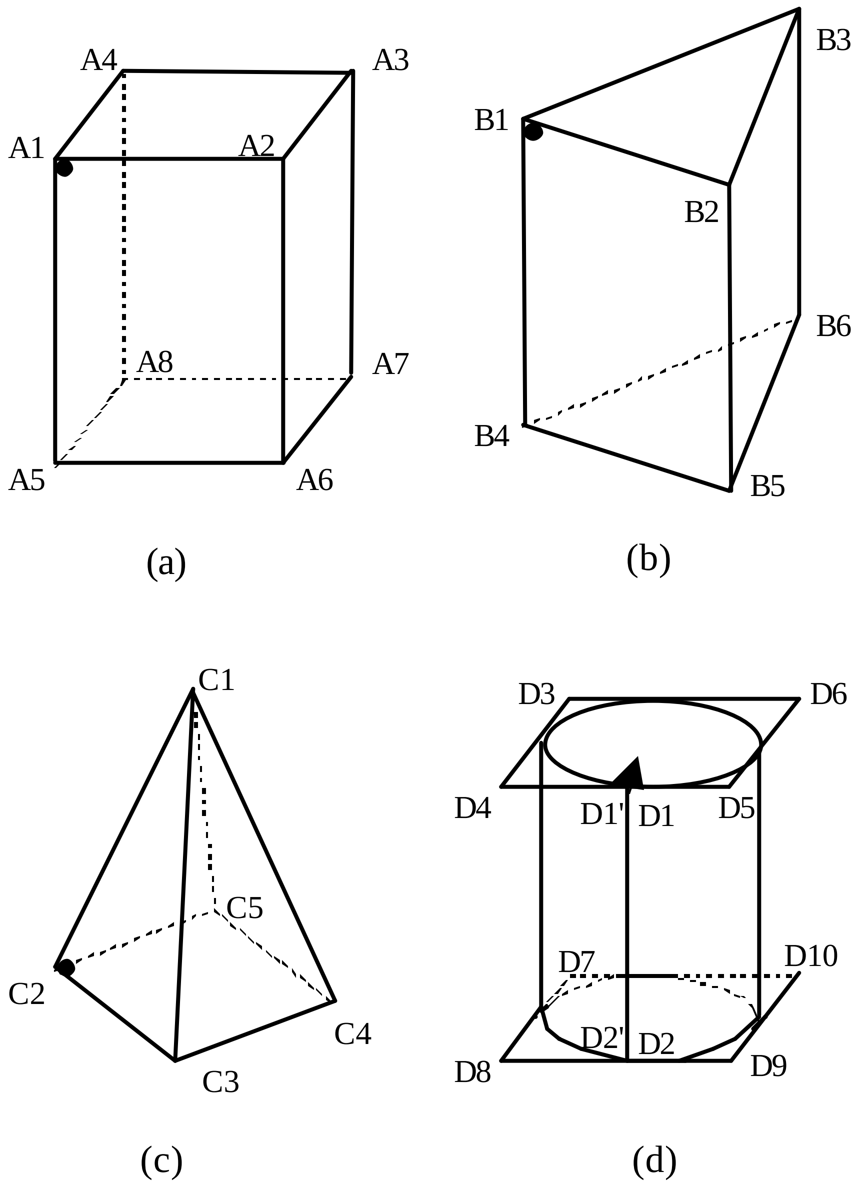




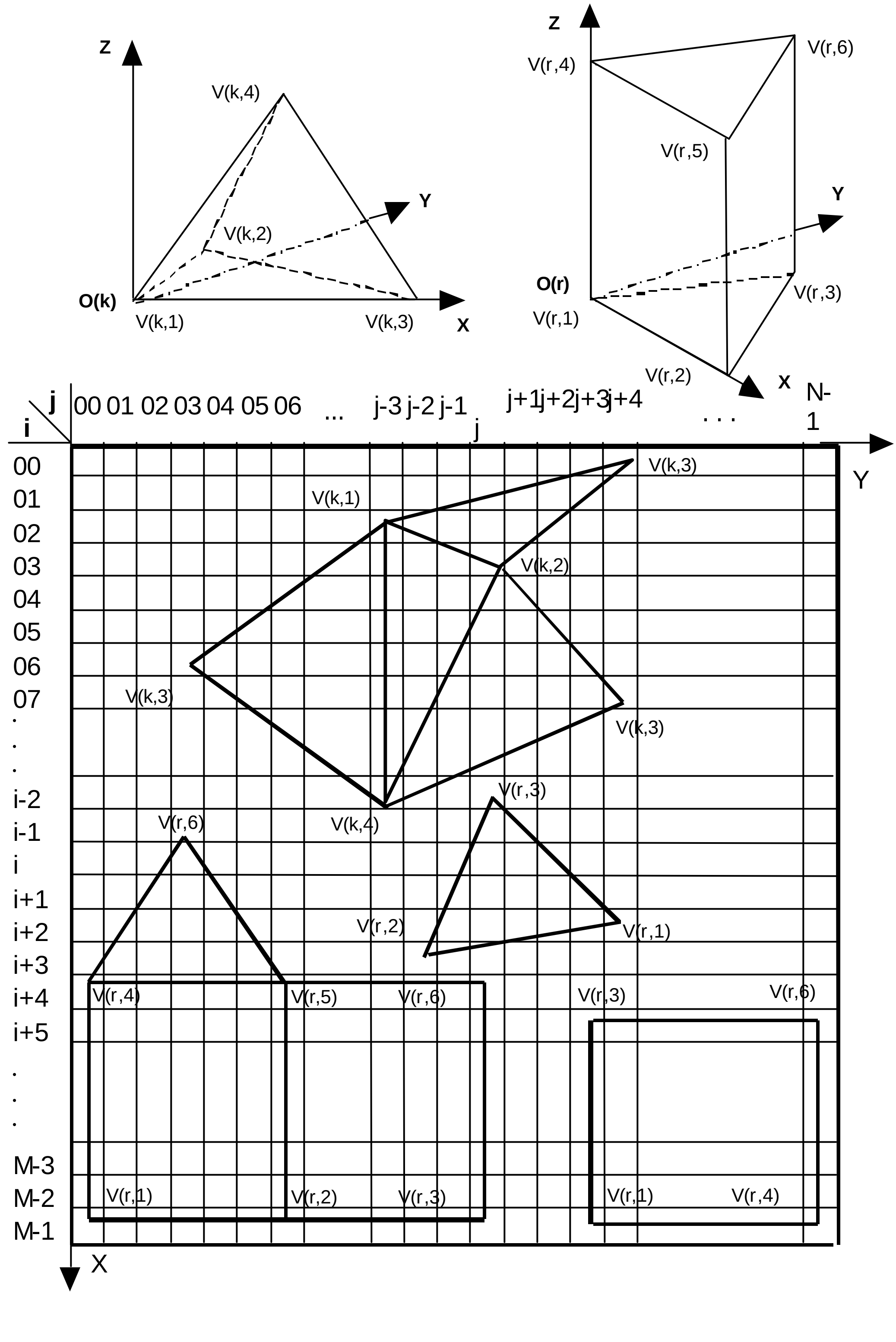
Computer vision recovery of the pseudo-random code

Model-based recognition of a pseudo-random encoded object

Model Based Object Recognition



The geometric model definition of four types of 3-D objects:
(a) rectangular parallelepiped, (b) triangular prism,
(c) square pyramid, and (d) right circular cylinder.

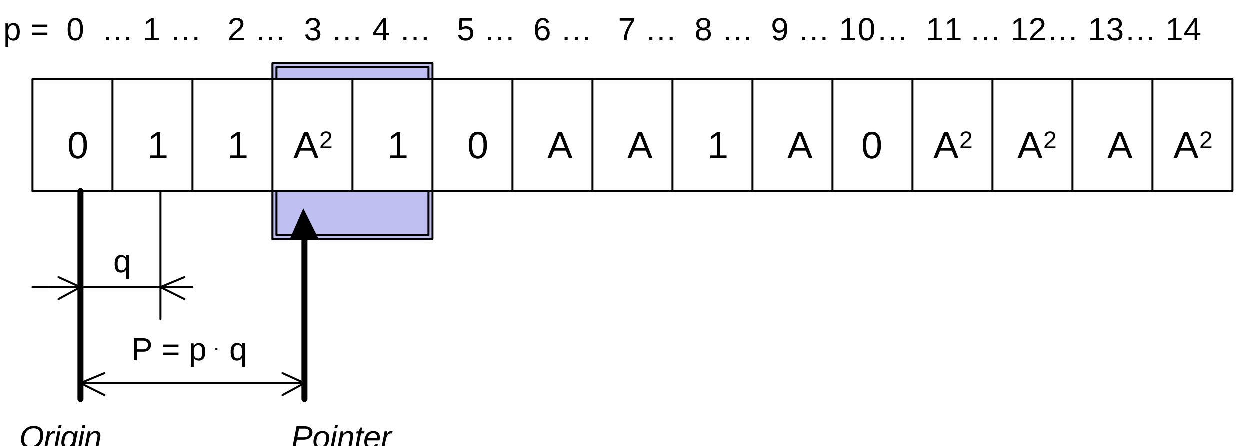


3D object models are unfolded and mapped on the encoding pseudo-random array.

Pseudo-Random Multi-Valued Sequences (PRMVS)

A more compact absolute position encoding can be obtained by using *Pseudo-Random Multi-Valued Sequences* (PRMVS) where sequence elements are entries taken from an alphabet with more than two symbols.

Compared to the traditional approach the resulting number of code tracks on the scale at the same resolution decreases proportionally with the size of the alphabet used.



As an example, a two stage shift register, n=2, having the feedback defined by the primitive polynomial $h(x)= x^2+x+A$ over GF(4) ={0,1,A,A^2}, with $A^2+A+1=0$ and A3=1, generates the 15-term PRMVS ***{0, 1, 1, A^2, 1, 0, A, A, 1, A, 0, A^2, A^2, A, A^2}.*** *Any 2-tuple seen through a 2-position window sliding over this sequence is unique.*

A "pseudo-random multi-valued sequence" (PRMVS) has multi-valued entries taken from an alphabet of q symbols, where q is a prime or a power of a prime. Such a (q^n -1) -term sequence is generated by an n-position shift register with a feedback path specified by a primitive polynomial

$$h(x) = x^n+h_{n-1}.x^{n-1}+...+h_1.x+ h_0$$

of degree n with coefficients from the Galois field GF(q).

When q is prime, the integers modulo-q form the Galois field GF(q)= {0,1,2,...,p-1} in which the addition, subtraction, multiplication and division are carried out modulo-q.
When q is a power of a prime, q=pm, the integers modulo-q do not form a field and the Galois field elements are expressed as the first q-1 powers of some primitive element, labeled here for convenience by the letter A: GF(q)= $\{0,1,A,A^2,...,A^{q-2}\}$.
The primitive polynomials used for different PRMVS generation depend on the nature of the addition/subtraction and multiplication /division tables adopted for each particular Galois field.

A number of primitive polynomials over GF(q) are given in the next Table for GF(3), GF(4), GF(8), and GF(9). It is obvious that the PRBS is a particular case of PRMVS for GF(2) ={0,1}.

n	*q=3*	*q=4*	*q=8*	*q=9*
2	x^2+x+2	x^2+x+A	x^2+Ax+A	x^2+x+A
3	x^3+2x+1	$x^3+x^{2}+x+A$	x^3+x+A	x^3+x+A
4	x^4+x+2	$x^{+}+x^2+Ax+A^2$	x^4+x+A^3	x^4+x+A^5
5	x^5+2x+1	x^5+x+A	$x^5+x^2+x+A^3$	x^5+x^2+A
6	x^6+x+2	x^6+x^2+x+A	x^6+x+A	x^6+x^2+Ax+A
7	$x^7+x^6+x^4+1$	$x^7+x^2+Ax+A^2$	$x^7+x^2+Ax+A^3$	x^7+x+A
8	x^8+x^5+2	x^8+x^3+x+A		
9	$x^9+x^7+x^5+1$	x^9+x^2+x+A		
10	$x^{10}+x^9+x^7+2$	$x^{10}+x^3+A(x^2+x+1)$		

The following relations apply:

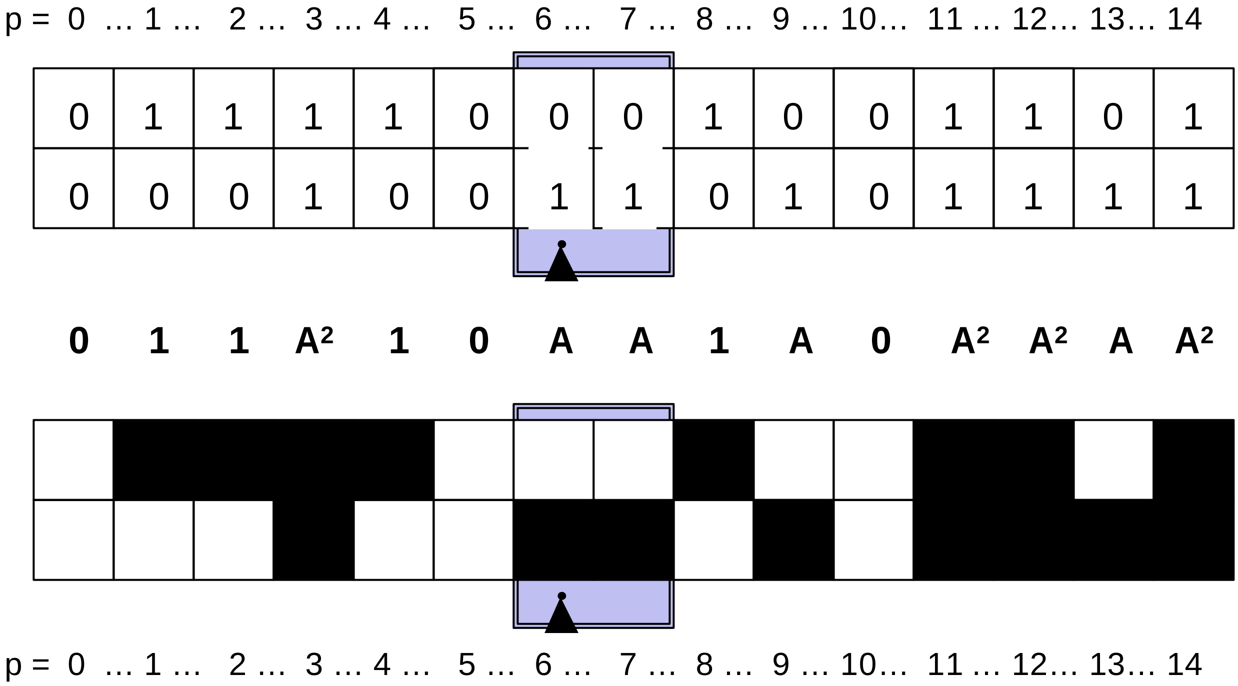
for $GF(4)=GF(2^2)$: $A^2+A+1=0$, $A^2=A+1$, *and* $A^3=1$

for $GF(8)=GF(2^3)$: $A^3+A+1=0$, $A^3=A+1$, $A^4=A^2+A$, $A^5=A^2+A+1$, $A^6=A^2+1$, *and* $A^7=1$

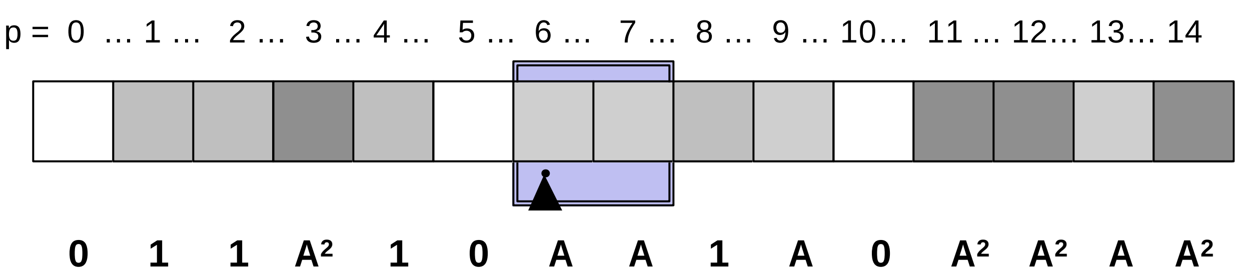
for $GF(9)=GF(3^2)$: $A^2+2A+2=0$, $A^2=A+1$, $A^3=2A+1$, $A^4=2$, $A^5=2A$, $A^6=2A+2$, $A^7=A+2$, *and* $A^8=1$

According to the PRMVS window property any q-valued contents observed through a n-position window sliding over the PRMVS is unique and fully identifies the current position of the window.

As an example, a two stage shift register, n=2, having the feedback path defined by the primitive polynomial $h(x)=x^2+x+A$ over $GF(4)=\{0,1,A,A^2\}$, with $A^2+A+1=0$ and A3=1, generates the 15-term PRMVS: **{0, 1, 1, A^2, 1, 0, A, A, 1, A, 0, A^2, A^2, A, A^2}.**
Any 2-tuple seen through a 2-position window sliding over this sequence is unique.



Implementation of a PRMVS encoded track using
***binary** code_markings & reading_heads (probes)*



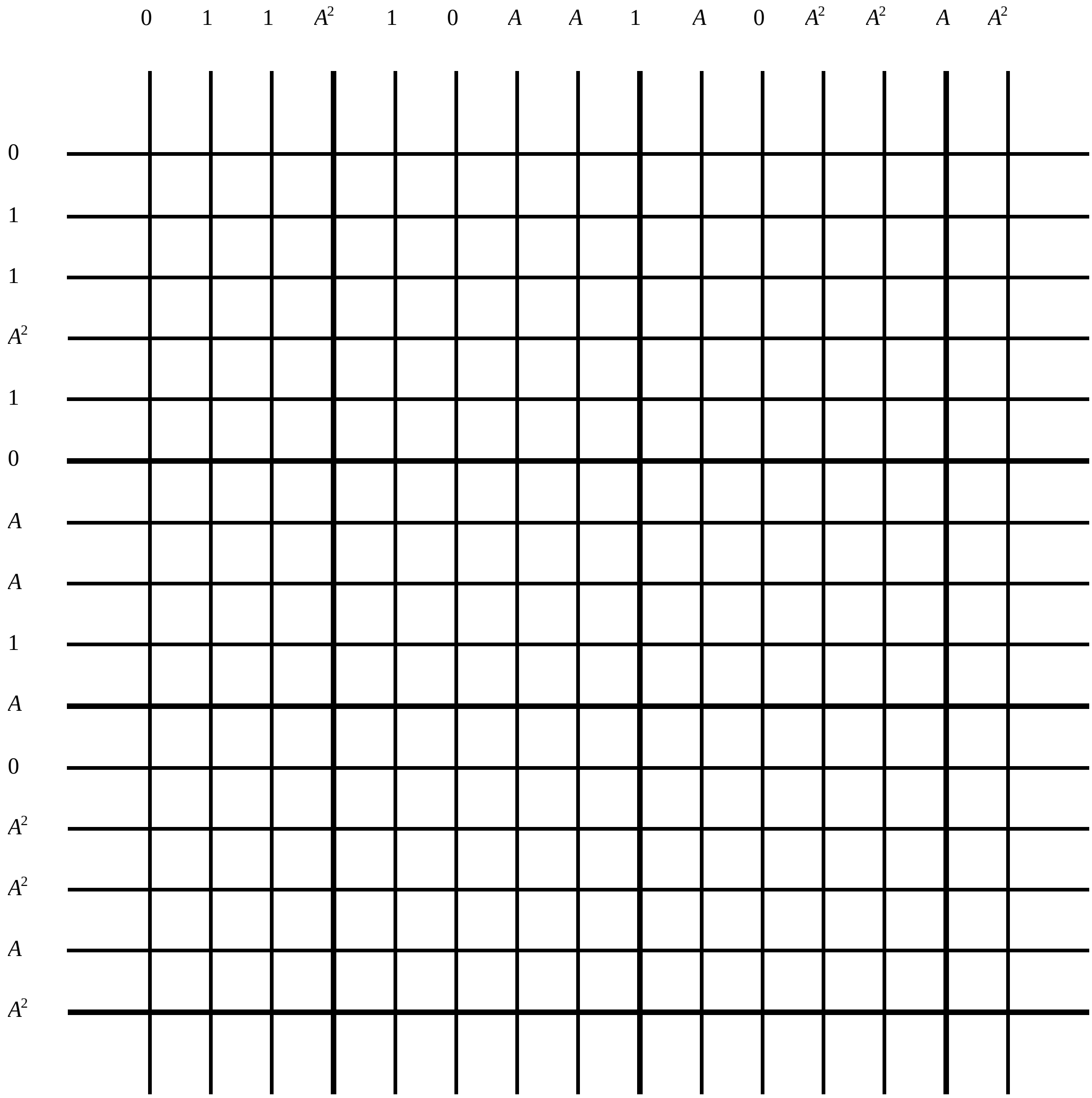
Implementation of a PRMVS encoded track using
***polyvalent** code_markings & reading_heads (probes)*

PRMVS Encoded Grid

The **rows** are encoded with the terms of a PRMVS $\{X(i) | i = 0,1,..., qx^{nx} - 1\}$ generated by a **nx** -stage shift register having entries taken from an alphabet of qx symbols.

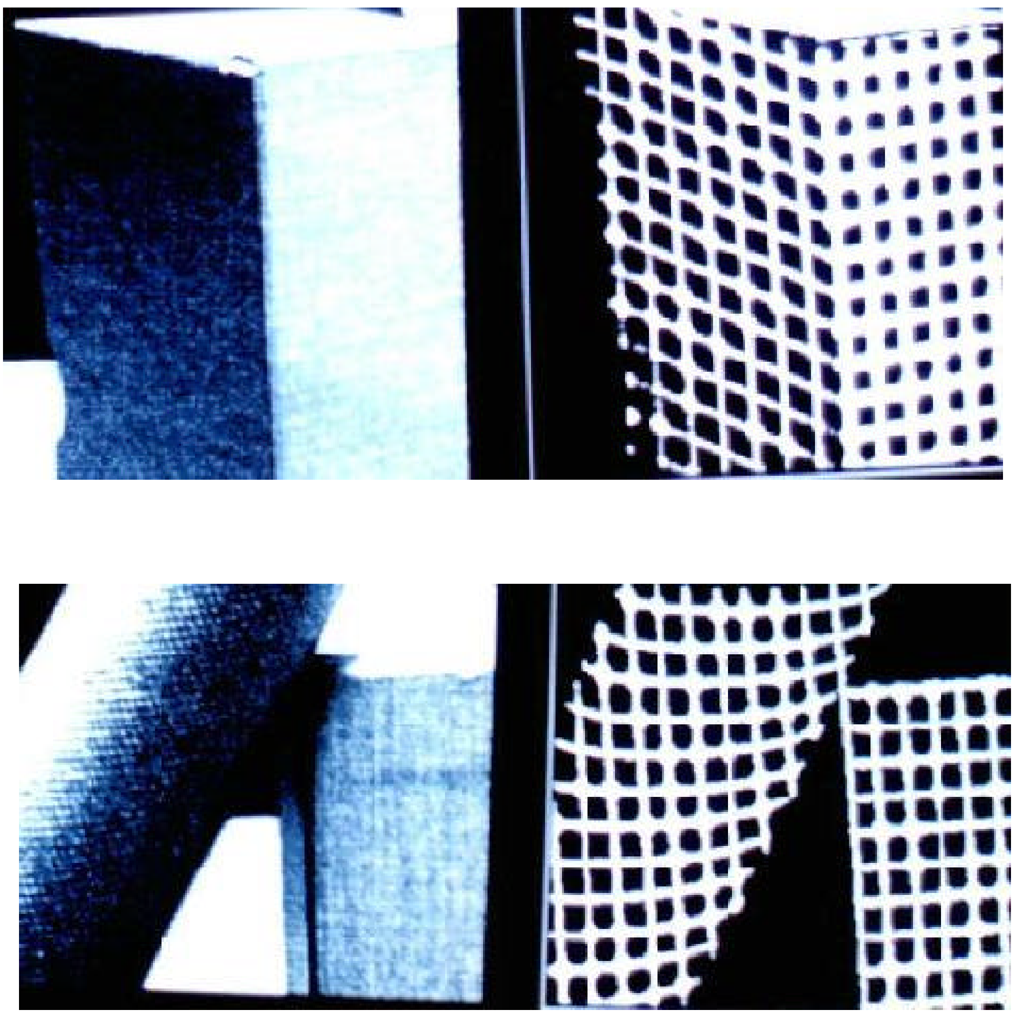
The **columns** are encoded with the terms of a PRMVS $\{Y(j) | j = 0,1,..., qy^{ny} - 1\}$ generated by a **ny**-stage shift register and having entries taken from an alphabet of qy symbols.

Absolute position recovery of any grid-node of coordinated (i,j) needs to identify a **nx-by-ny window**. The row-index **i** can be recovered if it is possible to identify a nx-tuple containing X(i). The column-index **j** can be recovered if it is possible to identify a ny-tuple containing Y(j).

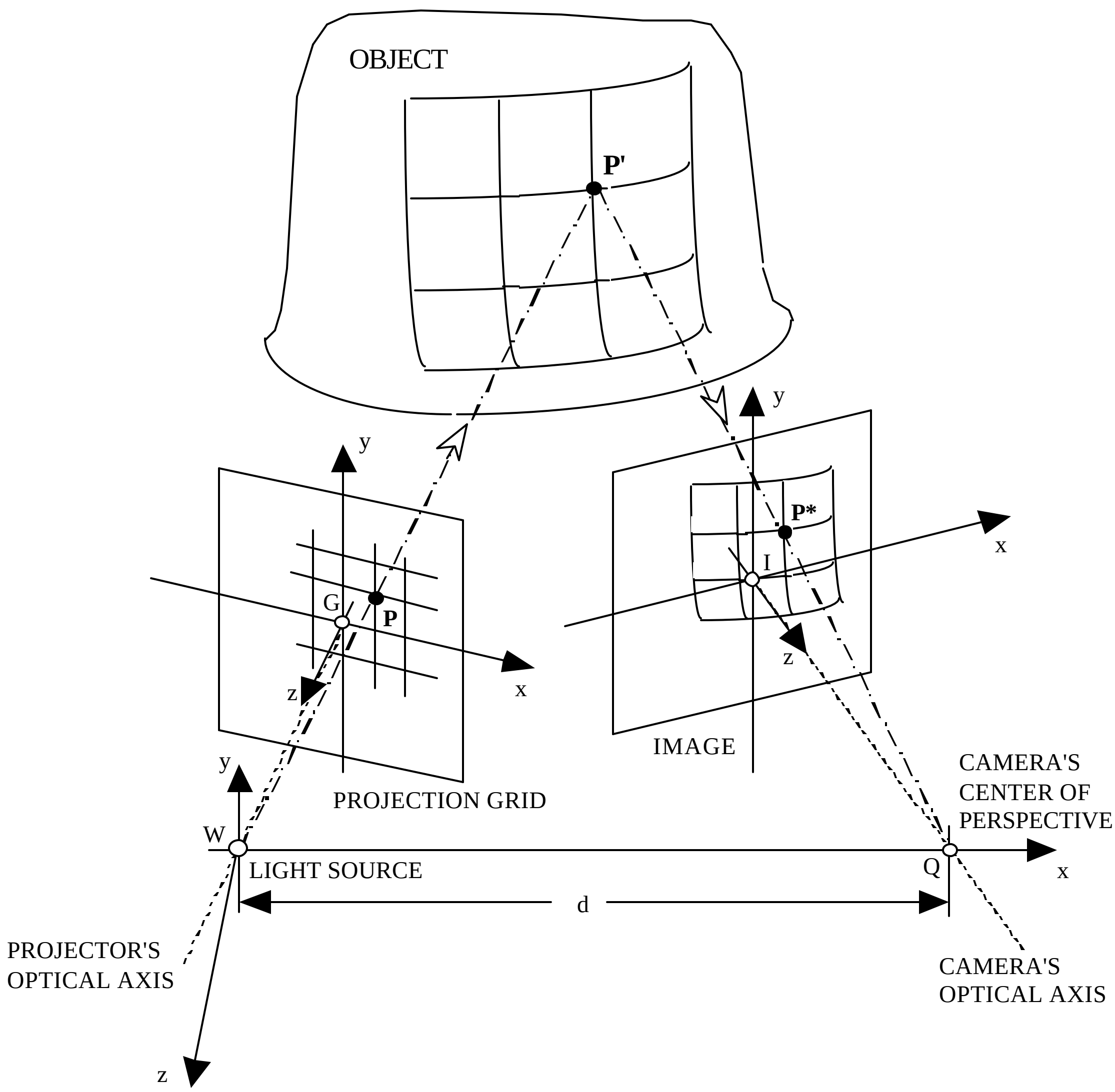


PRMVS grid having 15 row-lines and 15 column-lines encoded with the terms of two PRMVS $\{X(i)=Y(i)|\ i= 0,1,..., q^n -1\}$ where $q=4$ and $n=2$, defined over $GF(4)=\{0,1,A, A^2\}$. Absolute position recovery needs to identify a 2-by-2 window in this case. The row-index i of a given grid node (i,j) can be recovered if it is possible to identify the X(i) and X(i+1) [or X(i-1)] associated with two adjacent row lines. The column-index j of a given grid node (i,j) can be recovered if it is possible to identify the Y(j) and Y(j+1) [or Y(j-1)] associated with two adjacent column lines.

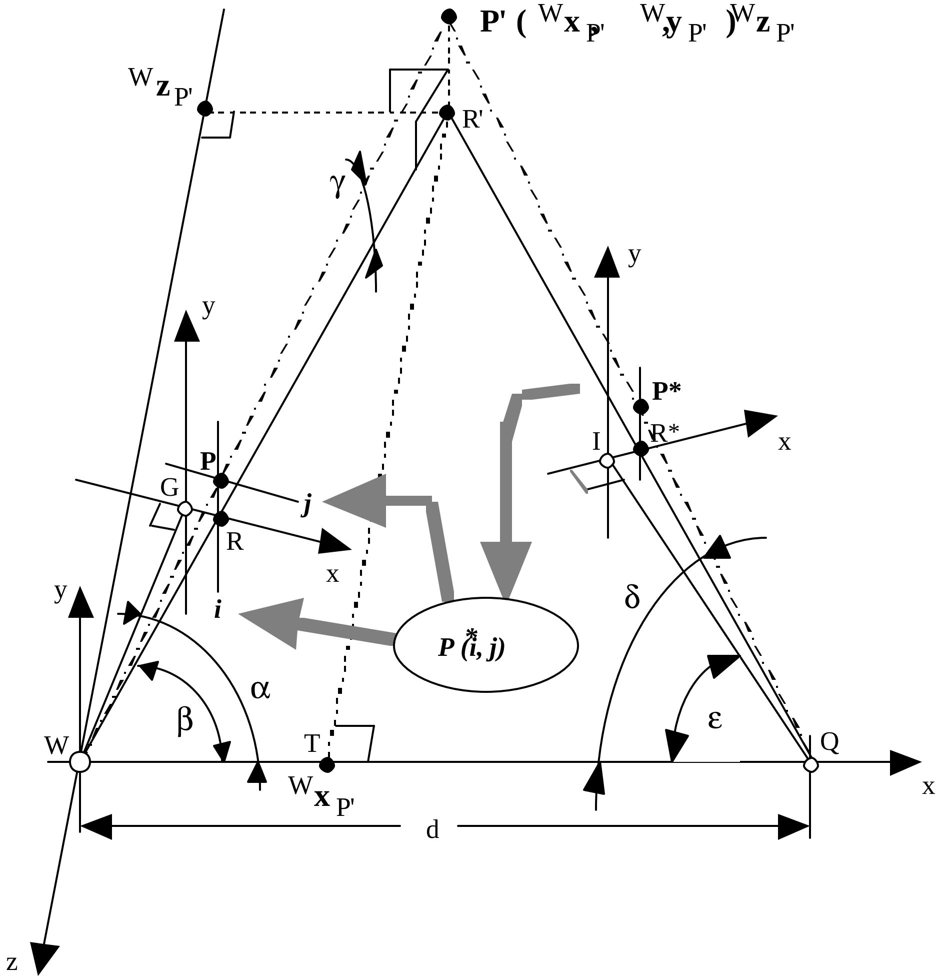
3D Object Recognition Using Structured Light



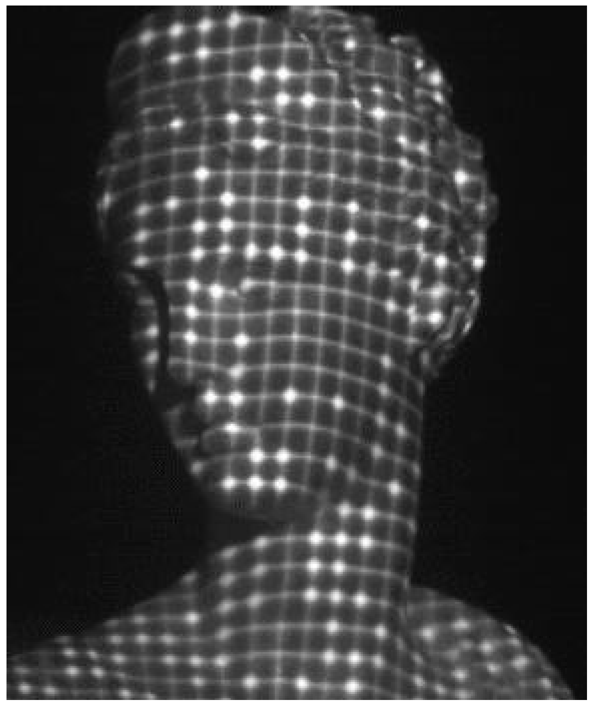
Recovery of the 3D shape of objects using structured light



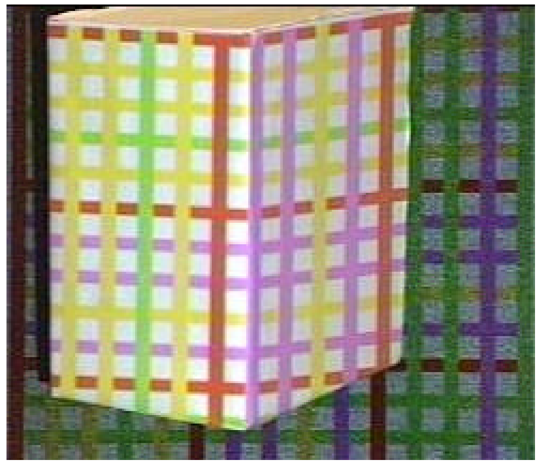
Point identification in pseudo-random encoded structured light



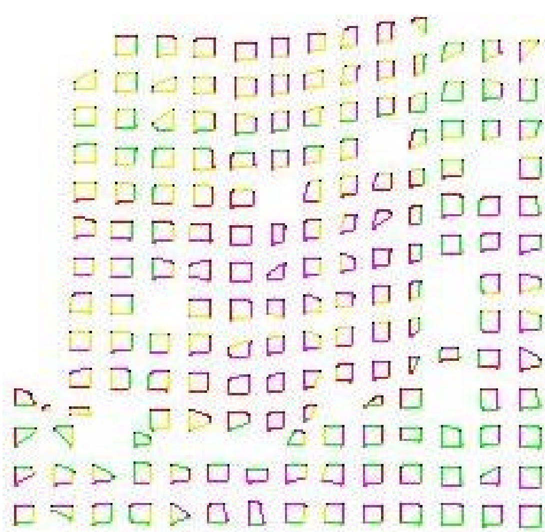
P' (Wx P' , Wy P' , Wz P')
Wz P'
R'
γ
y
y
P*
R*
I
x
P
G
j
R
x
y
i
P (i*, j)
δ
α
β
ε
W
T
Q
Wx P'
x
d
z



Pseudo-Random Binary Array encoded structured-light grid projected on a 3D object



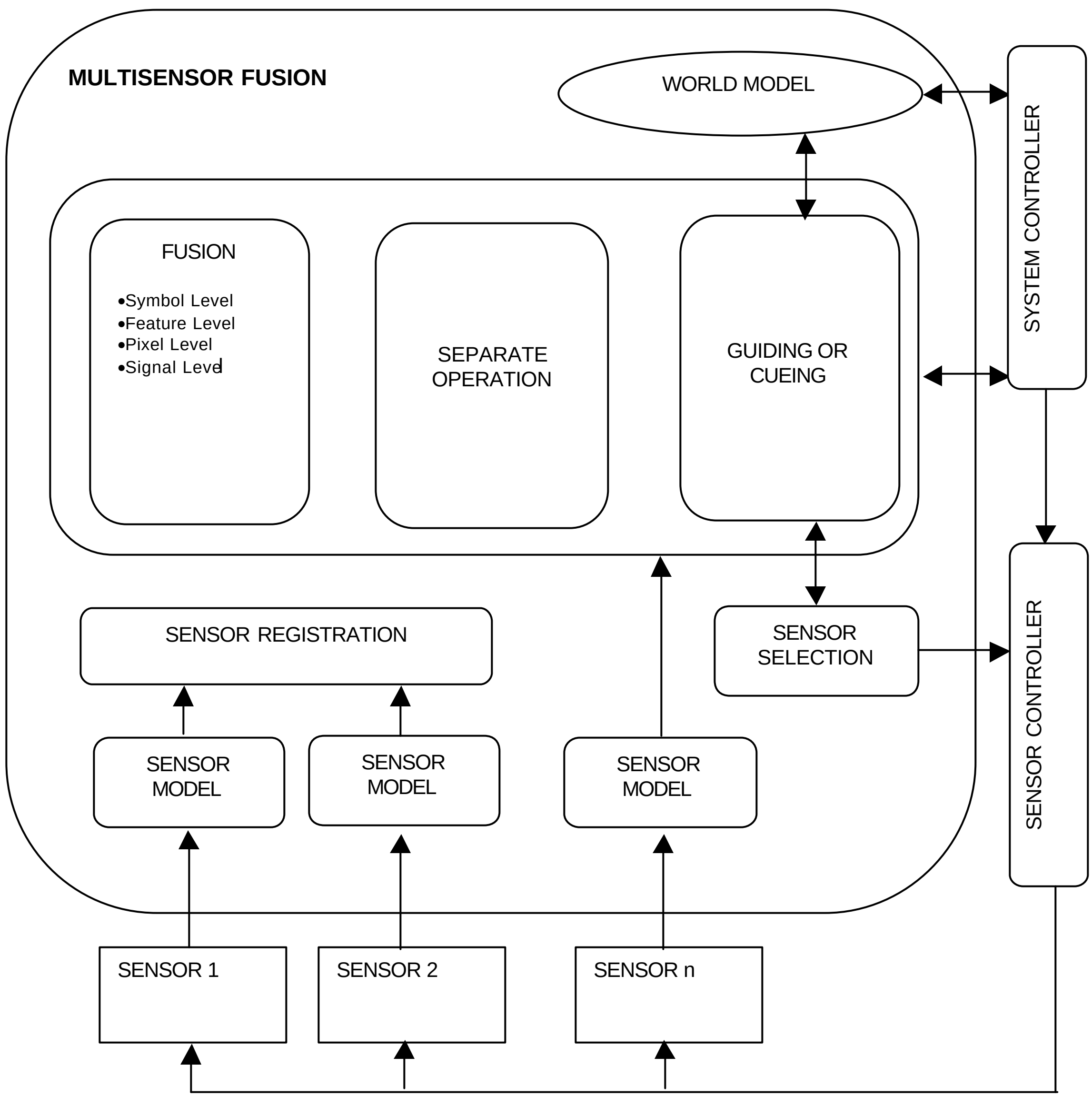
Pseudo-Random Multi Valued Sequence (PRMVS) opportunistically color encoded structured light grid projected on a cube



Recovered corner points at the intersection of grid line edges

Pseudo-Random Multi Valued Sequence (PRMVS) structured-light grid projected on a 3D object

Multisensor Data Fusion

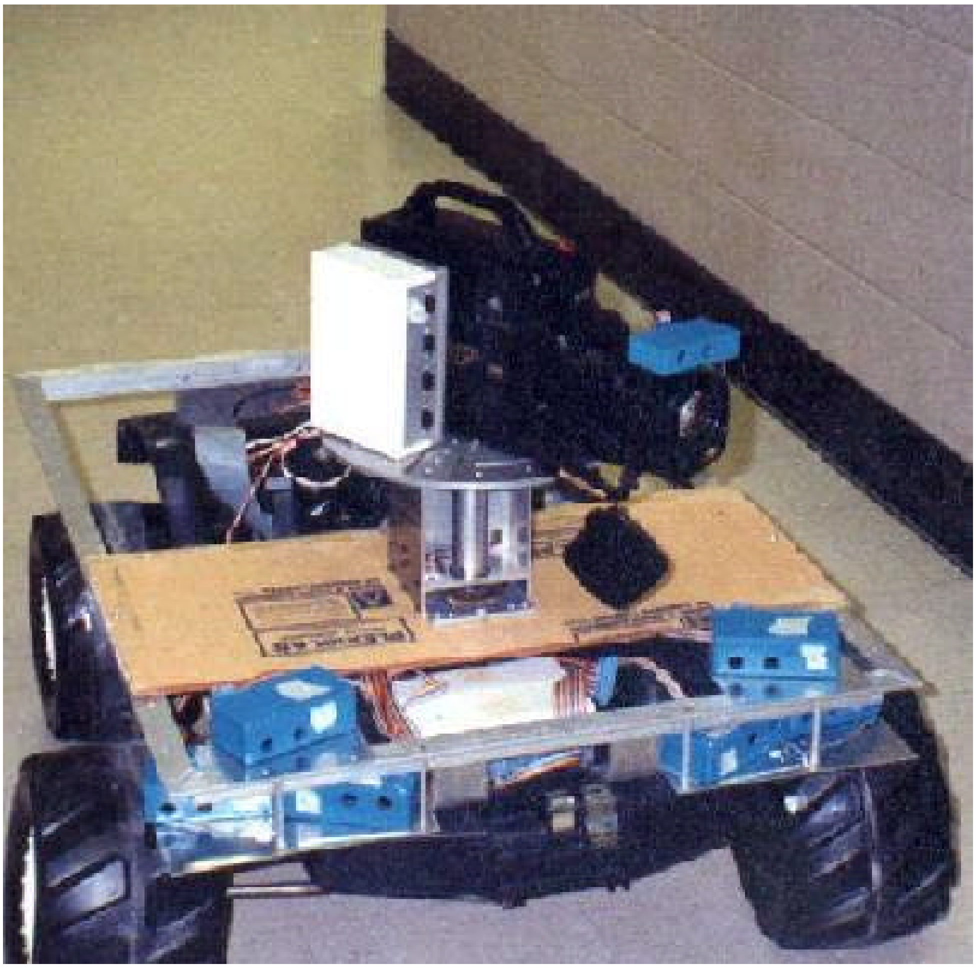


- ***Multisensor integration*** refers to the “synergistic use of the information provided by multiple sensors to assist the accomplishment of a task.”

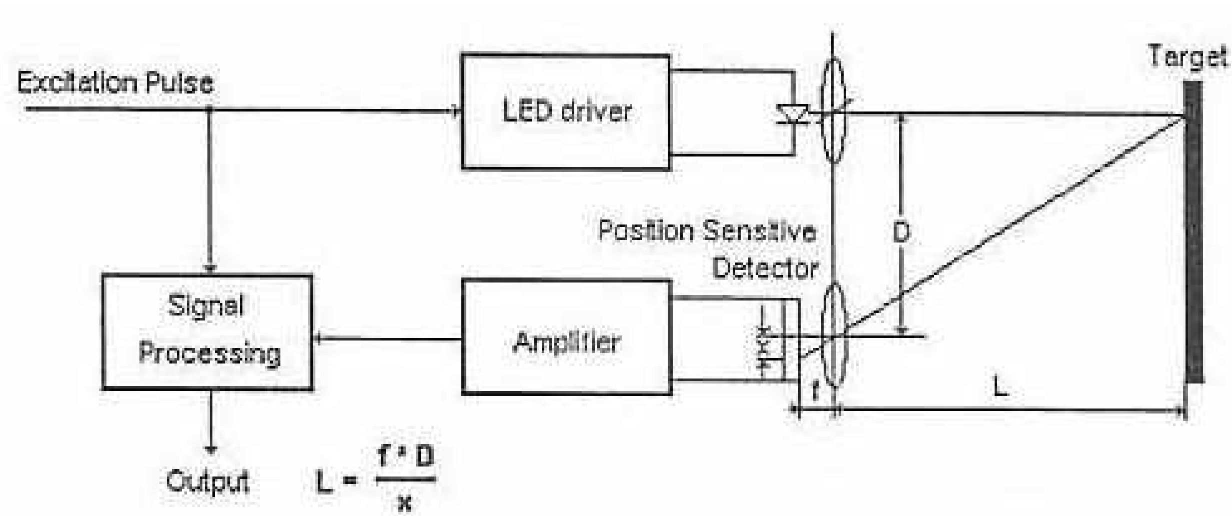
- ***Multisensor fusion*** refers to “any stage in the integration process where there is an actual combination (or fusion) of different sensor information into a unique representational format”.

Advantages of Multiple Sensors

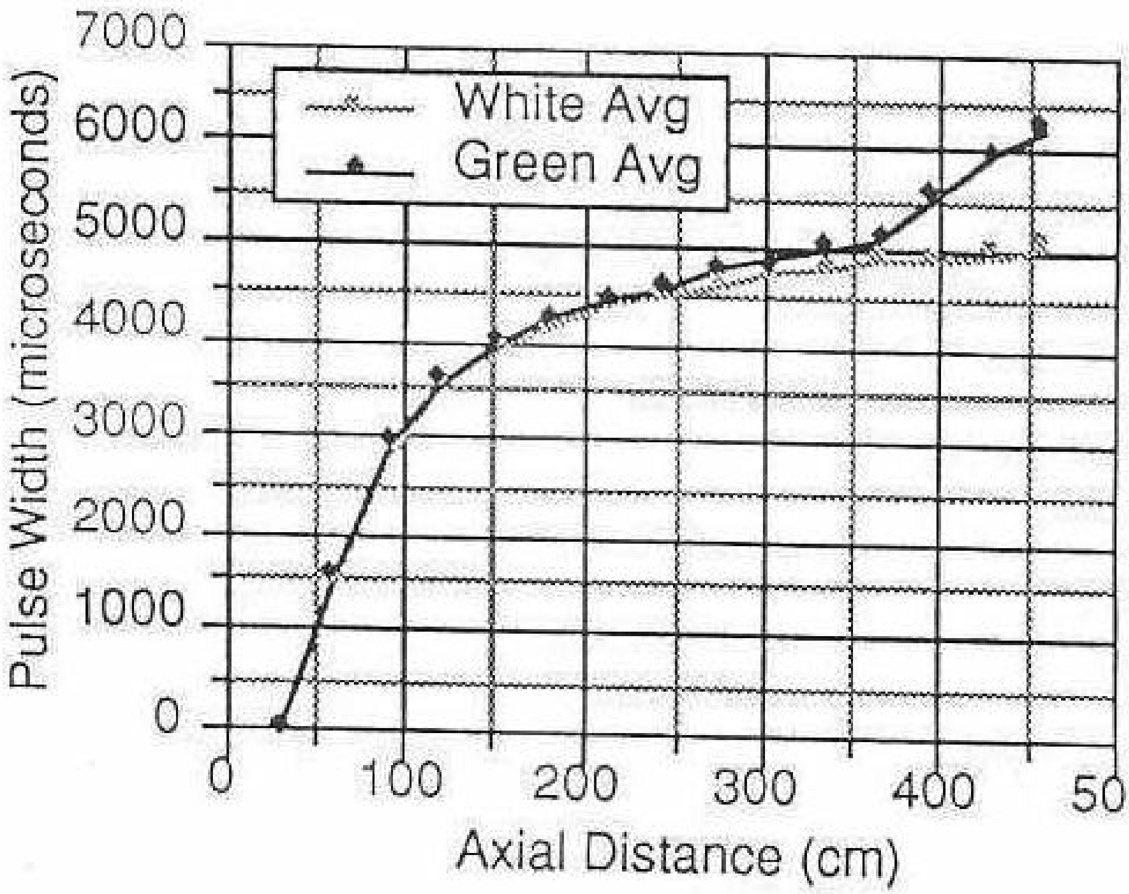
- ***Redundancy -*** Redundant information is provided from a group of sensors or by a single sensor over time when each sensor observes (possibly with different fidelity), the same features of interest
- ***Complementarity -*** Complementary information from multiple sensors allows for the perception of features that are impossible to be observed using just the information from individual sensors operating separately.
- ***Timeliness -*** More timely information may be provided by multiple sensors due to the actual speed of operation of each sensors, or to the processing parallelism that is possible to be achieved as part of the integration process.
- ***Cost*** - Integrating many sensors into one system can often use many inexpensive devices to provide data that is of the same, or even superior quality to data from a much more expensive and less robust device.



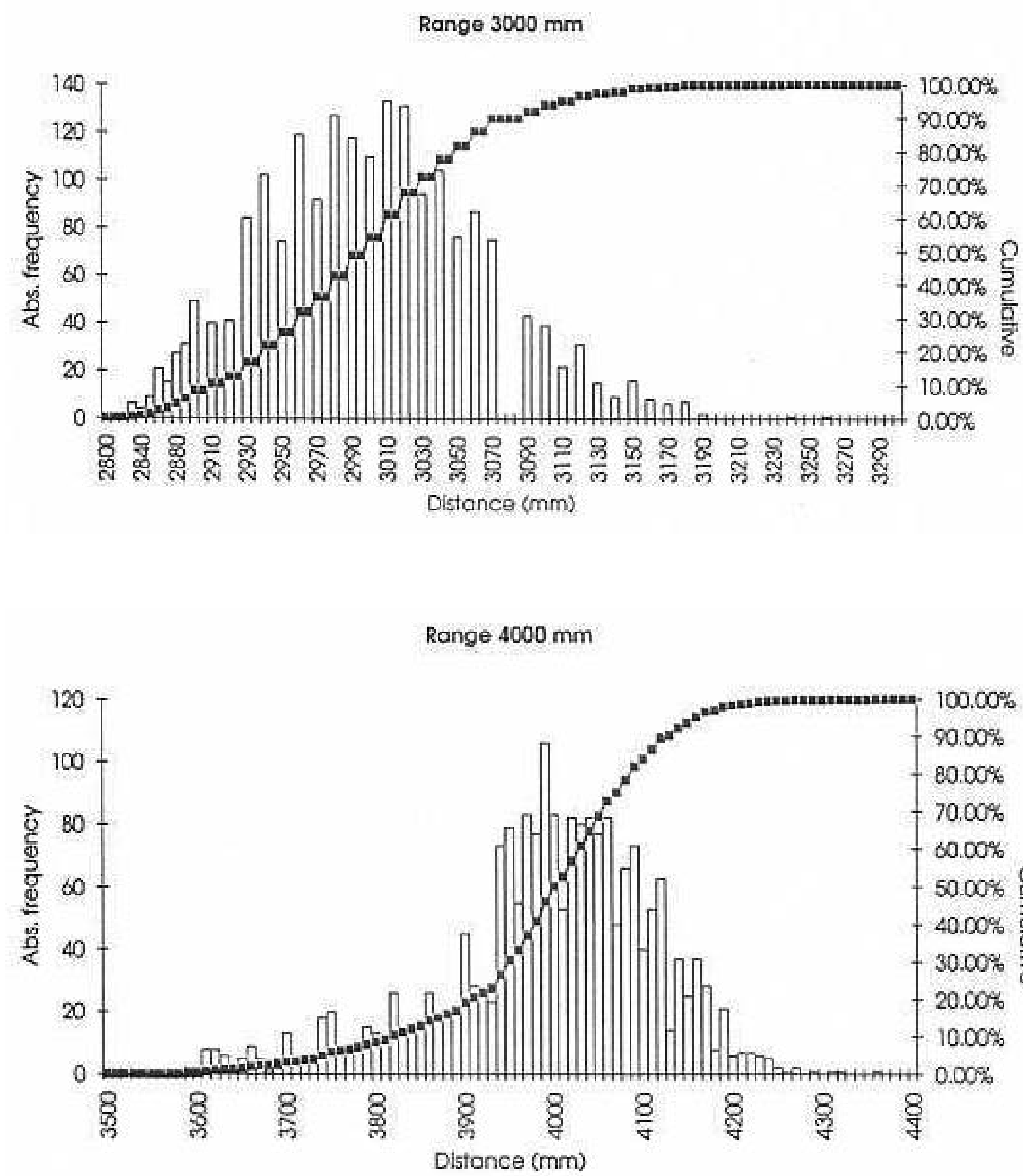
Mobile robot navigation using multiple IR sensors and vision



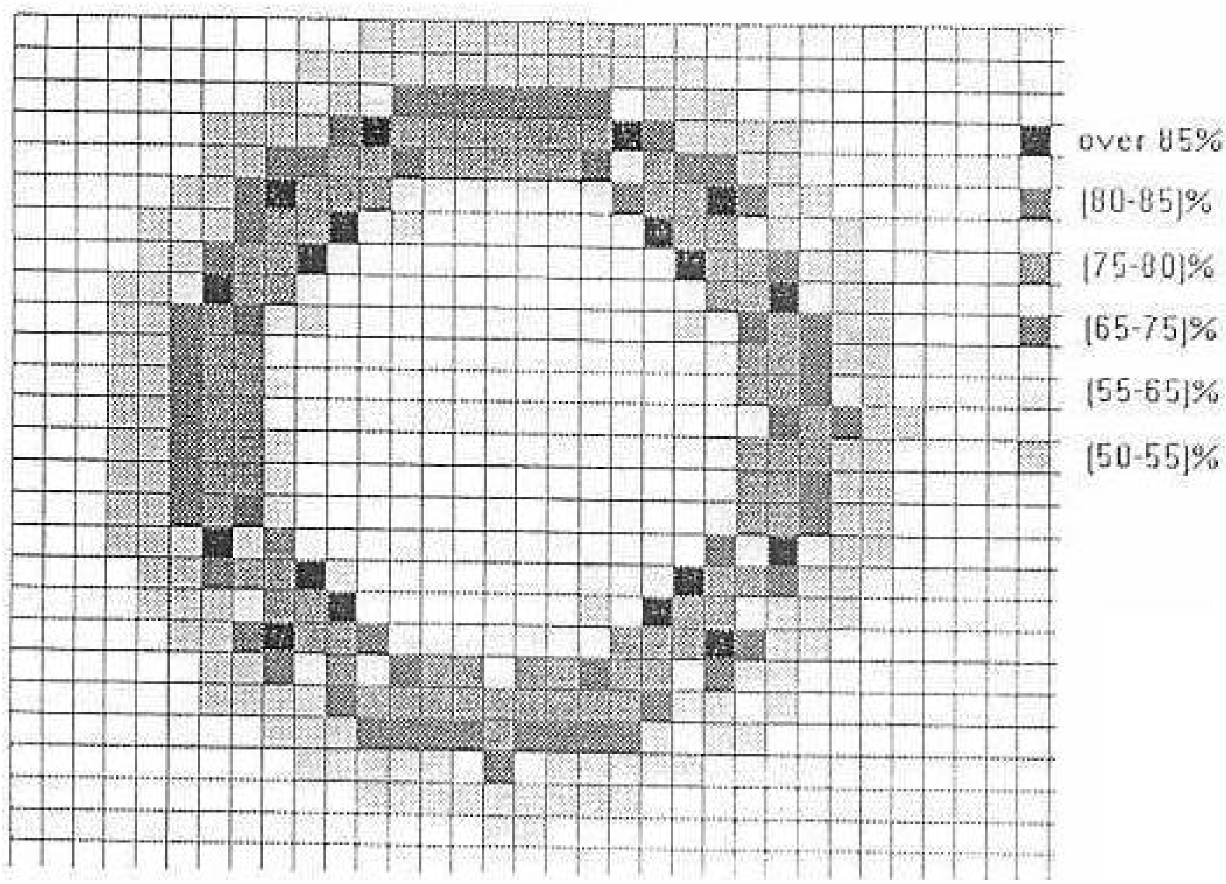
IR sensor based triangulation for Pentax Zoom 60x camera



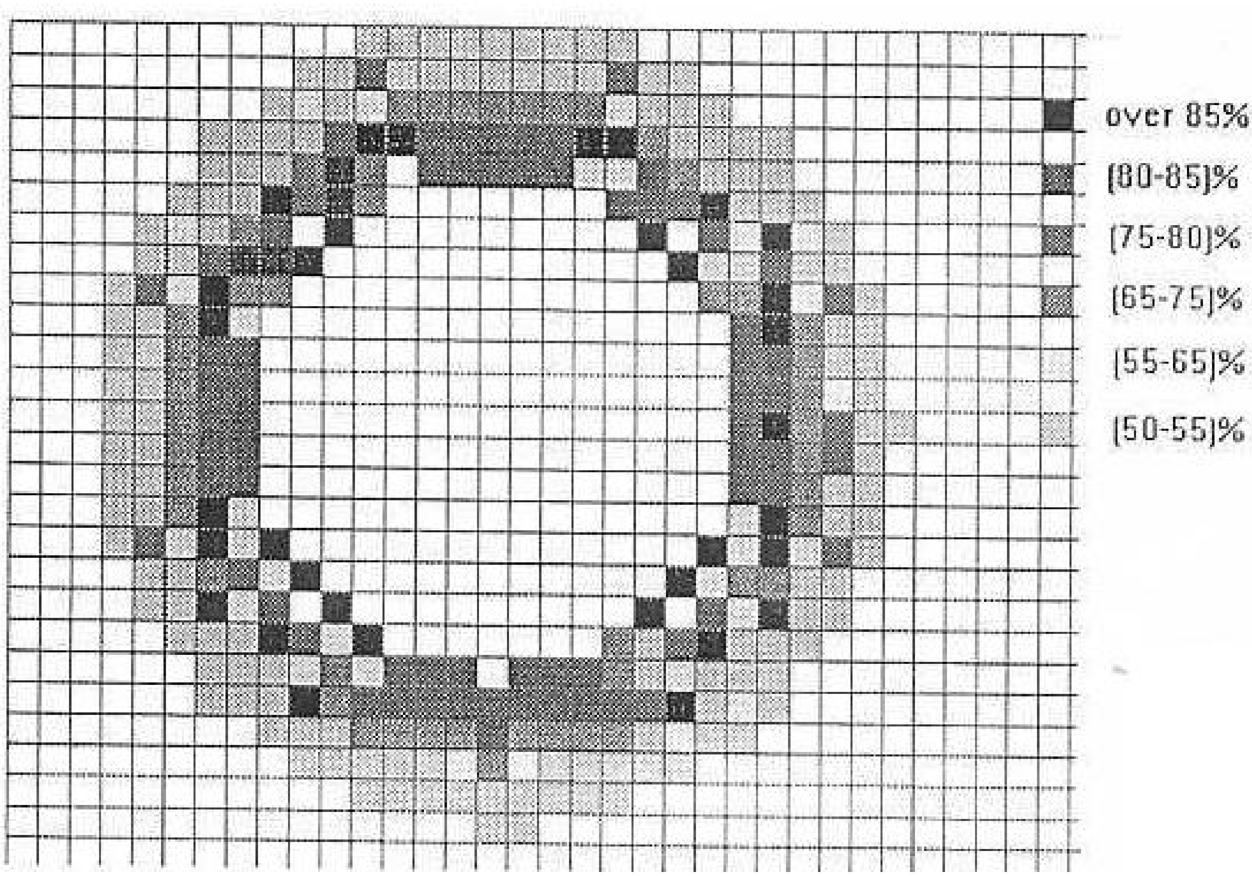
Axial characteristics for the IR sensor



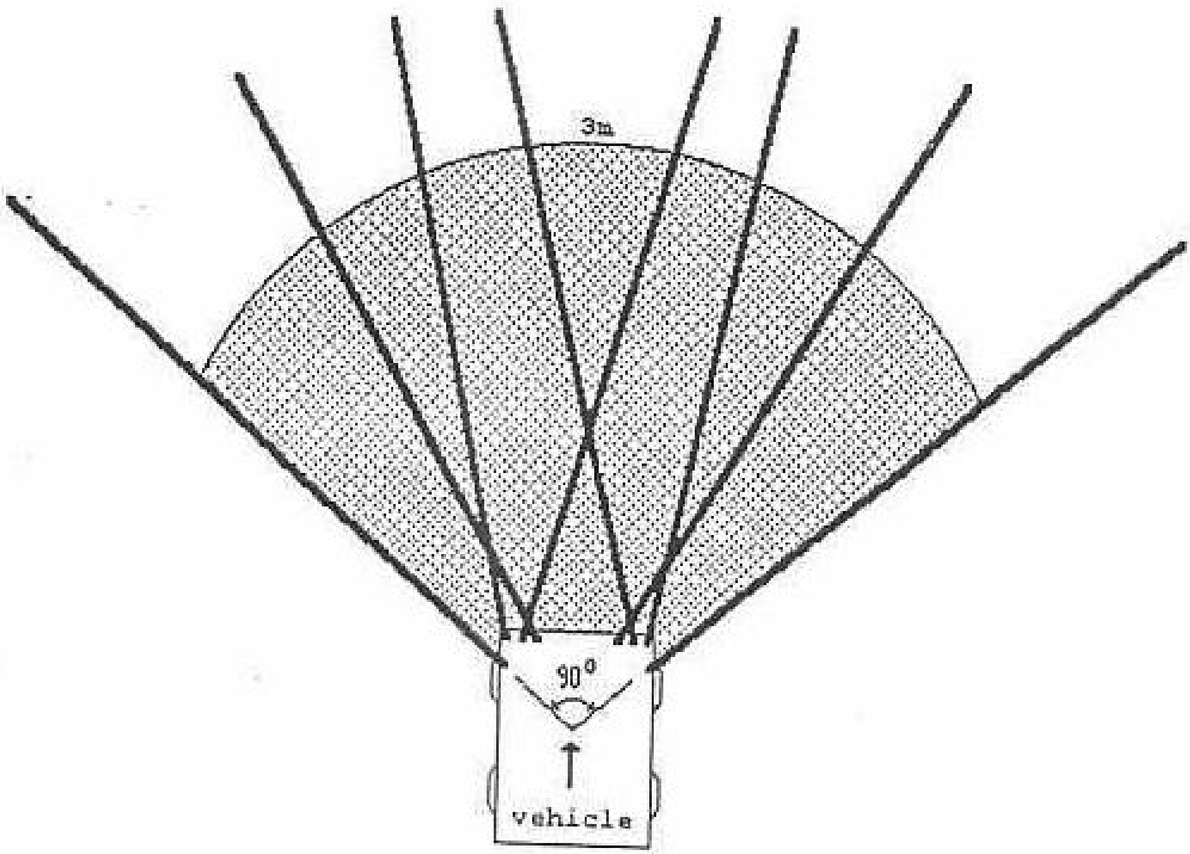
Probabilistic models of the IR sensor for two different measurement ranges



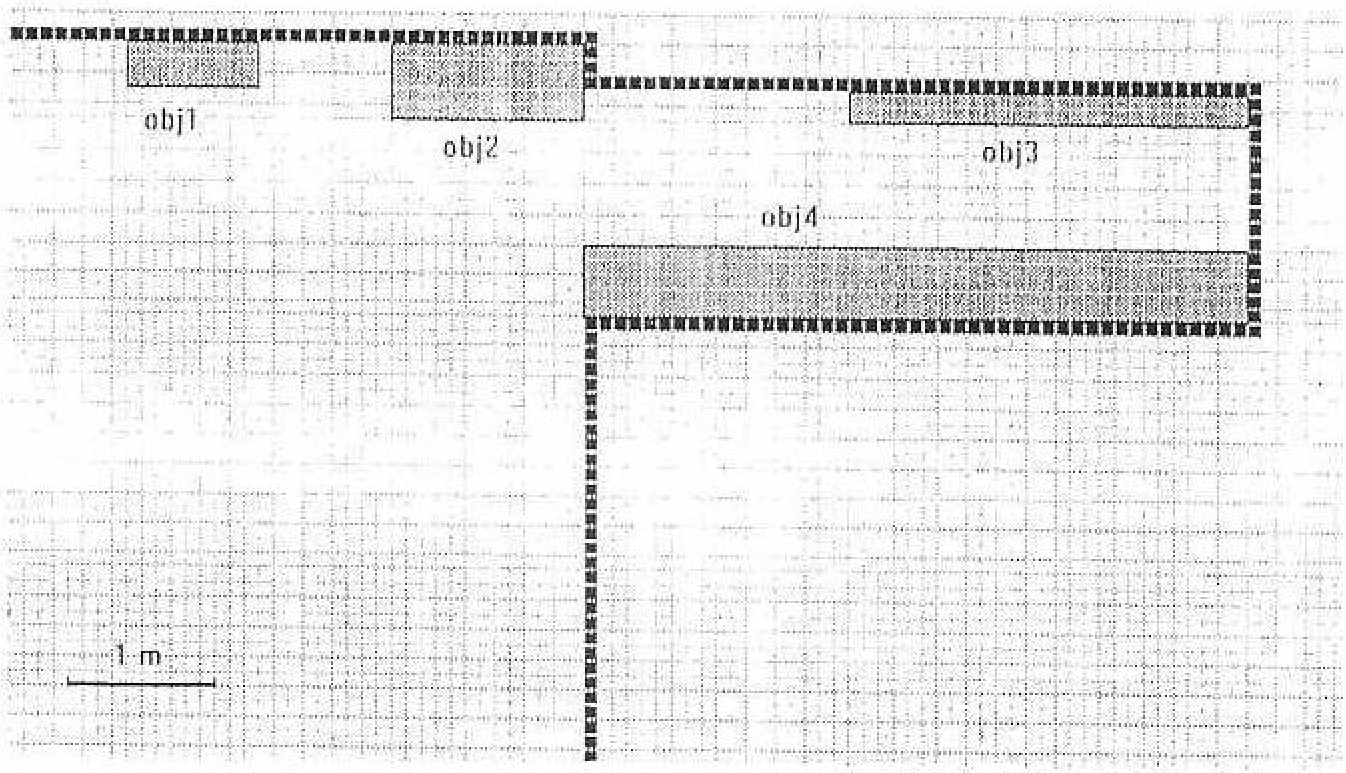
Occupancy grid map of of a round wall around the rotating IR sensor after one turn



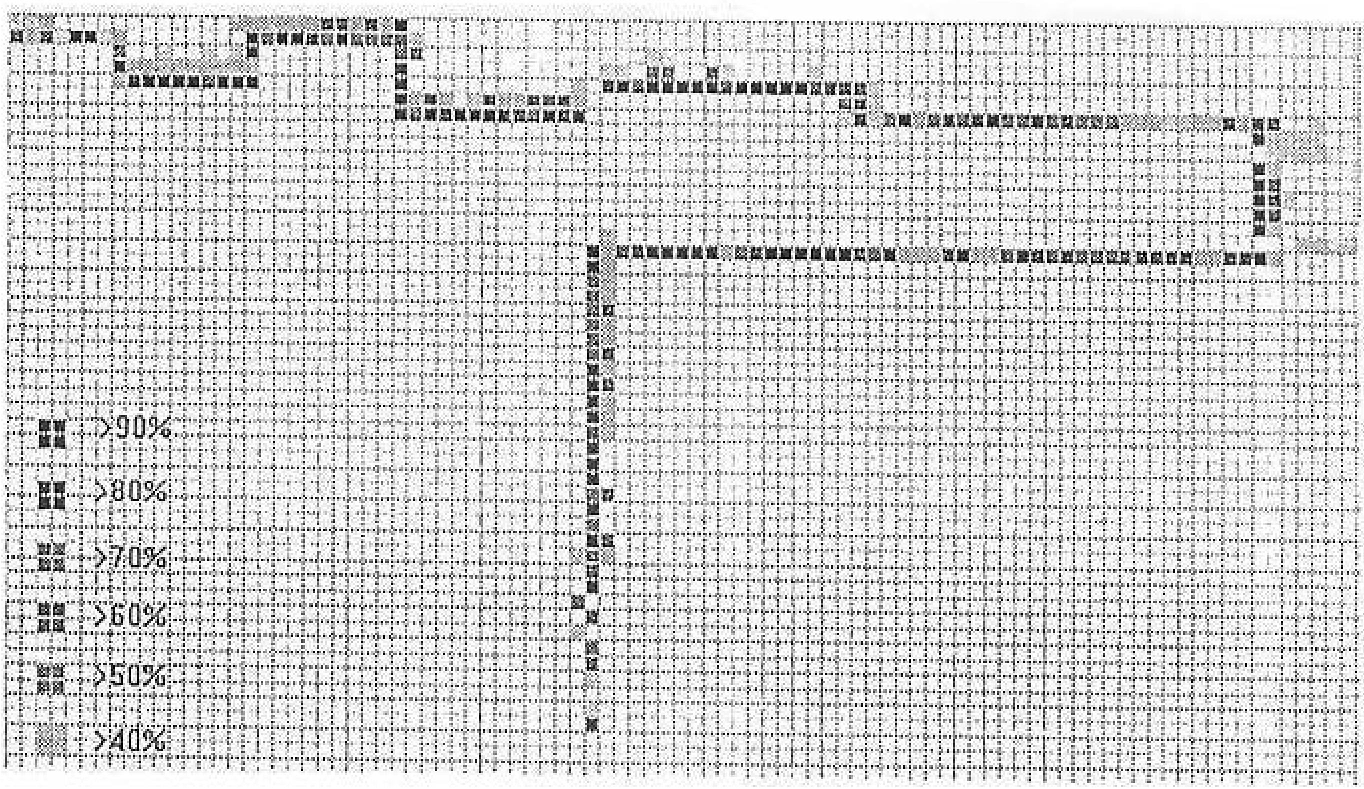
Occupancy grid map of of a round wall around the rotating IR sensor after ten turns



Multi IR sensor system on board the mobile robot



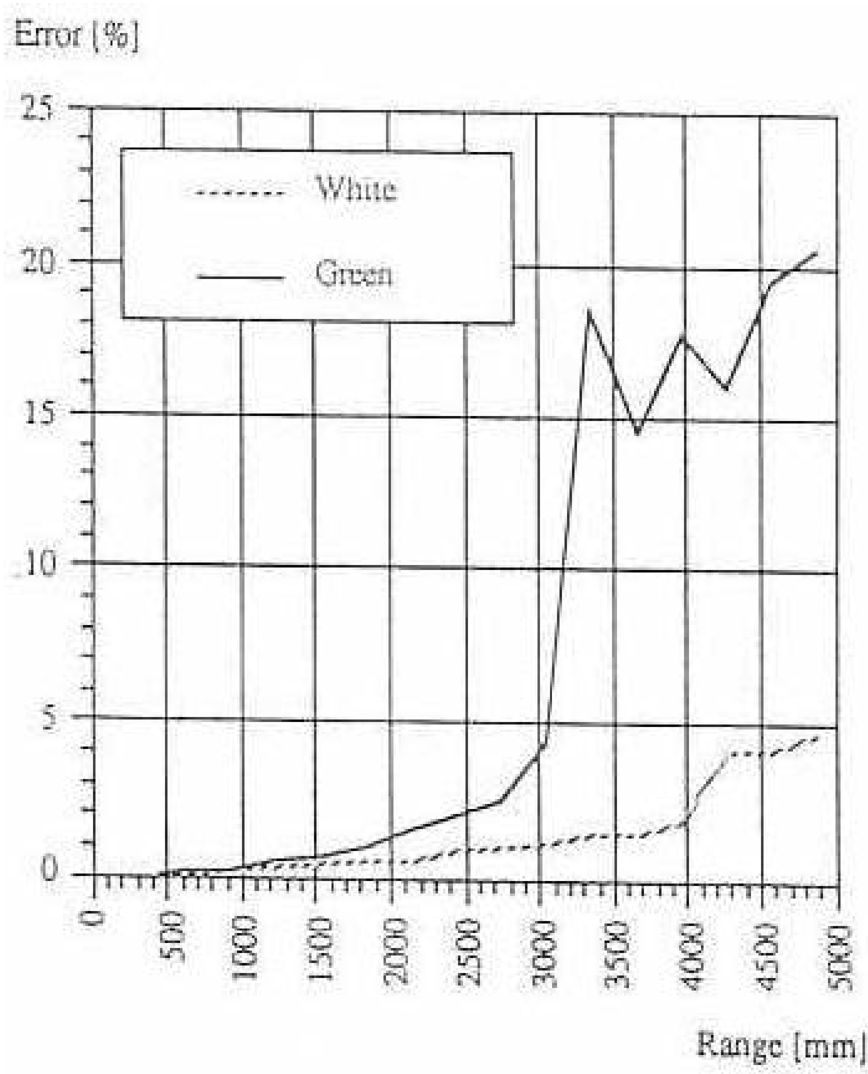
Layout of the room explored by the mobile robot with eight on board IR sensors



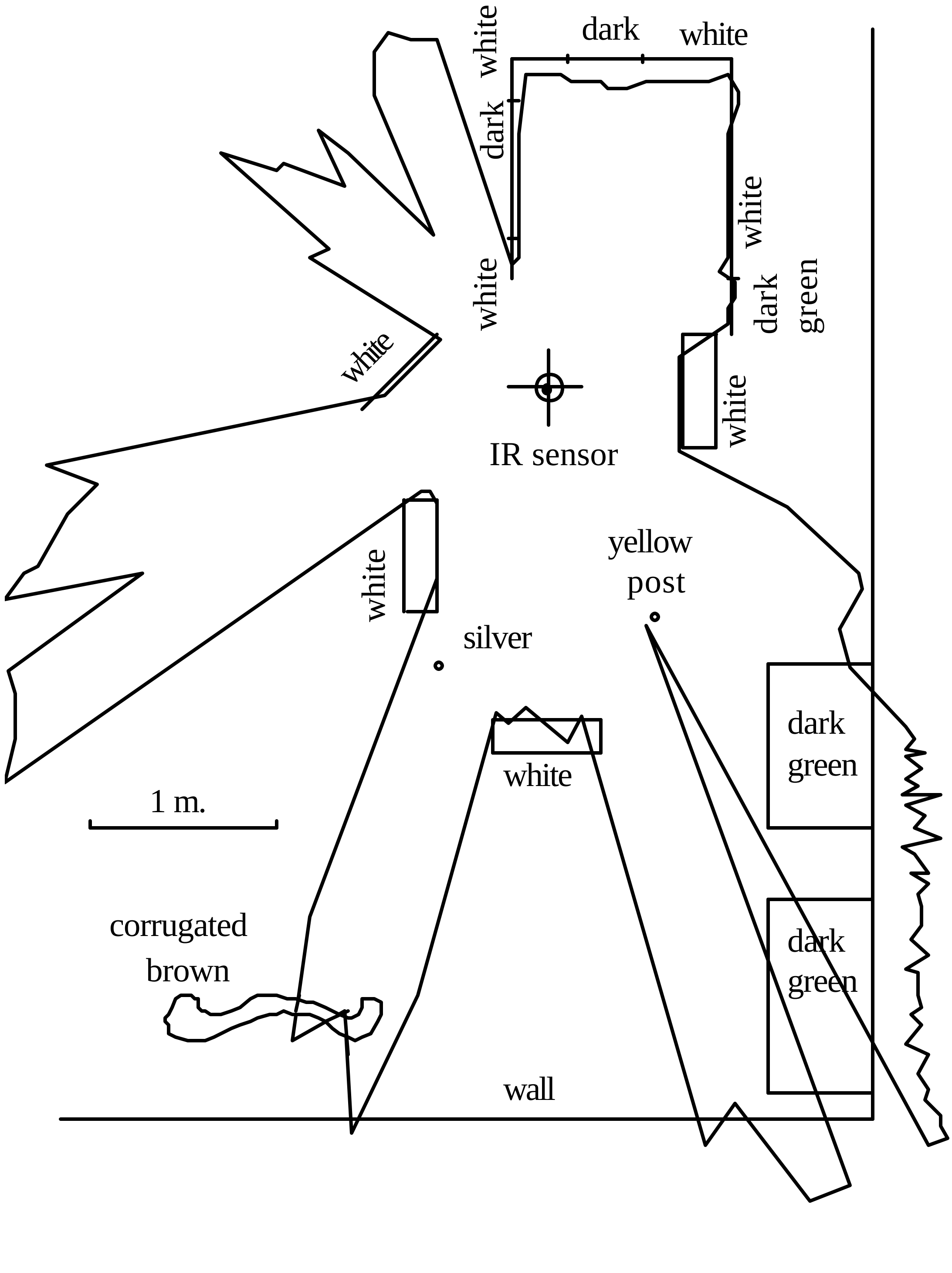
The recovered shape of explored room by fusing the data from the eight IR sensors using the probability occupancy grid method

Errors in Multisensor Systems

- ***Errors in the Integration and Fusion Process* –** a major source of errors when fusing redundant information from multiple sensors is the sensor registration
- ***Errors in the Sensory Information-*** usually are assumed to be caused by a random noise (uncorrelated in space or time, Gaussian and independent) that can be adequately modelled as a probability of distribution. The consistency of sensor measurements is increased by eliminating the spurious measurements so that they are not included in the fusion process.
- ***Errors in the System Operation* -** A multisensor system must have the ability to recognize and recover from sensor failure. Sometimes in unknown environments, it may be difficult or impossible to calibrate sensors. A solution would be the creation of a knowledge database for each sensor permitting an auto-calibration process of the system.



Error characteristics of the IR sensor for two colors of the targets


white
dark
white
dark
white
white
dark
green
white
white
IR sensor
yellow
post
white
silver
white
1 m.
dark
green
dark
green
corrugated
brown
wall