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An Optimized Version of a New Absolute Linear Encoder Dedicated to Intelligent Transportation Systems

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Abstract: - This paper proposes an optimized version of a new absolute linear encoder (ALE). The innovative ALE can be used for long distance applications (more then 150m) and the accuracy of the measurements is 0.5mm. To obtain these performances the ALE uses a new coding algorithm. This new coding algorithm is the core of the ALE and it allows an economical device solution. The optimized version is able to measure a double distance (more then 300m) with a better accuracy (0.25mm). These performances are obtained using the same device, the same number of sensors and the same ALE structure. The only changes were made in the coding algorithm, in the ruler topology and in the dedicated software. The optimized ALE is a robust device able to work in industrial environment, with a high level of vibrations. By this reason it is ideal for the transport system control in automating manufacturing processes, intelligent storage spaces, huge archives and libraries

Key-Words: - linear absolute encoder, multiple codification, permutation coding, binary coding, linear motor optical fiber sensor, coded strip, intelligent transportation system

1 Introduction

In an intelligent transportation system precise knowledge of the position of the moving parts is an essential requirement. When the traction system uses linear motors, a positioning system is used to control the linear motor feed. There are many types of absolute linear encoders (ALE): digital encoders (using binary or Gray code), analog encoders (inductive, capacitive, resistive, Hall, piezoelectric or Doppler, laser or radar)[1]. Usually, these types of ALE are designed to measure short distances (~1m) with high accuracy (<0.1μm) [2]. Some Doppler encoders are designed for long distance applications, but they have two important disadvantages: first, the Doppler encoders can work only in straight-line and second, the response time limits the speed of the moving part. In Table 1 the characteristics of a few Doppler encoders for long distances are shown. [3]

	Wenglor Sensoric	Sick	Pepperl Fuchs	Visolux
Type	XT200 MGV80	DME 2000	OCD20M F5-IE2	EDM120 DWA120

Scanning	0.3-20.7m	0.1-130m	0-20m	0.5-120m
Method	Retri-reflective	Retri-reflective	Retri-reflective	Retri-reflective
Measuring range	20m	129.9m	20m	119.5m
Response time	8 ms	10 ms	50 ms	0.5 ms
Laser light	LTT mode	LTT mode	LTT mode	LTT mode
Beam spot diameter	5mm at 1m	250mm at 130m	400mm at 20m	300mm at 130m
Resolution	10mm	1mm	40mm	0.1mm
Accuracy	±3%	2mm	±2%	±0.5mm

Table 1. Principal characteristics of Doppler long distance encoders

The most popular ALE is the digital encoder. For this type the binary coding is used. In the case of binary coding, the number of binary words n_w is defined by:

$$n_w = \frac{L}{\Delta l} \qquad (1)$$

where L is the displacement length and Δl is the accuracy demand.

All n_w binary words have the same number of bits n_b, where:

$$n_w \le 2^{n_b} \qquad (2)$$

For these conditions, if the displacement is 9 meters and the required accuracy is 0.5mm, to achieve this by using binary coding, natural or Gray, 15 optical sensors and 15 optical tracks are necessary[3]. A typical structure of an absolute binary encoder, comprising optical sensors and coded strips (for 4 bits binary words) is shown in Fig.1.

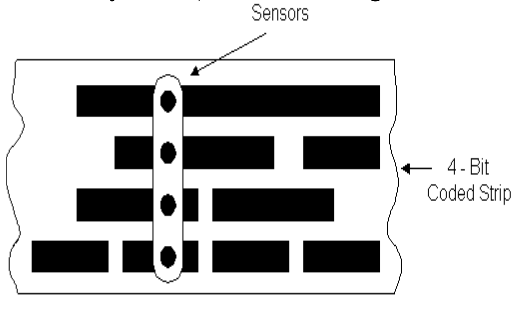

Fig.1. An absolute binary encoder (optical sensors and the coded strip)

2 Theoretical aspects of the new absolute linear encoder

An intelligent transportation system with linear motors has the topology shown in Fig.2.

Typical applications of length encoders include long distance transportation lines (>100m). Binary coding cannot offer an economic implementation. For this reason the paper proposes a new coding method. This method uses a combination of 3 coding strategies: binary coding, permutation coding and length coding. To illustrate the principle of the new coding method, a simple example is given.

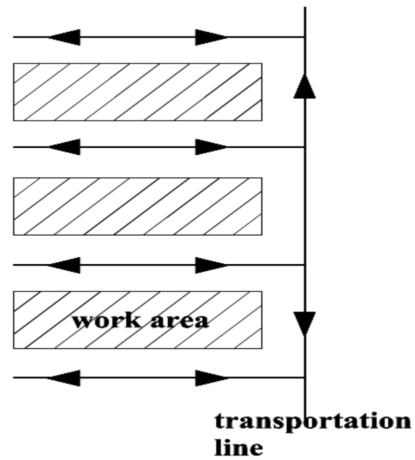

Fig.2. Topology of a transportation line

First, the total distance is divided into equal elementary steps. The step is 40 mm length. Then, the elementary step is divided into 3 different mini-steps A,B and C, where A+B+C=40mm (e.g. A=7mm, B=13mm and C=20mm). The mini-steps A,B,C are arranged according to the combinational rules. With 3 elements A,B,C it is possible to obtain maximum 3!=6 permutations: (A, B, C); (A, C, B); (B, C, A); (B, A, C); (C, A, B) and (C, B, A). If the binary coding is applied to all mini-steps and we accept the notation A,B,C for logic 1 and a,b,c for logic 0, the initial set of permutations becomes: ABC; ABc; AbC; Abc; aBC; aBc; abC; abc; ACB; ACb; AcB; Acb; aCB; aCb; acB; acb; BAC; BAc; BaC; Bac; bAC; bAc; baC; bac; BCA; BCa; BcA; Bca; bCA; bCa; bcA; bca; CAB; CAb; CaB; Cab; cAB; cAb; caB; cab; CBA; CBa; CbA; Cba; cBA; cBa; cbA; cba. In this way, using 3 mini-steps of different length, binary coding and the permutation rules, it is possible to encode 48 steps. The maximum distance that can be coded in this way is: 48 steps x 40mm=1920mm.

2.1 The complete new ALE for long distance

Three mini-steps only are insufficient to design an absolute linear encoder for measuring a long distance. The number of mini-steps must be chosen taking account of the necessary coding length. Suppose a distance of 100m is to be measured, and the elementary step size is 40 mm. Then the

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necessary number of mini-steps is 5, A,B,C,D,E. The length of the mini-steps are: L_A = 4mm, L_B = 6mm, L_C = 8mm, L_D = 10mm L_E = 12mm.

With 5 mini-steps, the maximum number of permutations is 5! = 120: {A, B, C, D, E}, {A, B, C, E, D}, {A, B, D, C, E}, {A, B, D, E, C}, {A, B, E, C, D},{A, B, E, D, C}, {A, C, B, D, E}, {A, C, B, E, D}, {A, C, D, B, E}, {A, C, D, E, B},{A, C, E, B, D}, {A, C, E, D, B}, {A, D, B, C, E}, {A, D, B, E, C}, {A, D, C, B, E},{A, D, C, E, B}, {A, D, E, B, C}, {A, D, E, C, B}, {A, E, B, C, D}, {A, E, B, D, C},.……., {E,D,B,C,A},{E,D,C,A,B},{E,D,C,B,A}

If binary coding is used, for each combination of 5 mini-steps it is possible to obtain 32 new combinations (because $2^5 = 32$). In this way, starting with the initial combination {A,B,C,D,E} and using the same notation convention A, B, C, D, E = logic 1, and a, b, c, d, e = logic 0, the 32 new combinations are, [4]:

{A,B,C,D,E}{A,B,C,D,e},{A,B,C,d,E},{A,B,C,d,e},{A,B,c,D,E},{A,B,c,D,e},{A,B,c,d,E},{A,B,c,d,e},{A,b,C,D,E},{A,b,C,D,e},{A,b,C,d,E},{A,b,C,d,e},{A,b,c,D,E},{A,b,c,D,e},{A,b,c,d,E},{A,b,c,d,e},{a,B,C,D,E},{a,B,C,D,e},{a,B,C,d,E},{a,B,C,d,e},{a,B,c,D,E},{a,B,c,D,e},{a,B,c,d,E},{a,B,c,d,e},{a,b,C,D,E},{a,b,C,D,e},{a,b,C,d,E},{a,b,C,d,e},{a,b,c,D,E},{a,b,c,d,E},{a,b,c,D,e},{a,b,c,d,e}

The distance between two combinations is a 40 mm step. The total number of combinations is $120 \times 32 = 3840$, the total number of coded steps. The maximum coded length now becomes: $3840 \times 40 = 153600\,mm$. The maximum number of coded steps as a function of the number of mini-steps is: [5]

$$n_s = n_{ms}!\,2^{n_{ms}} \qquad (3)$$

$n_s =$ number of coded steps

$n_{ms} =$ number of mini- steps

Every coding strategy, comprising length, binary code, and permutation, requires a special track on the new coded strip. The coded strip of the proposed ALE contains 4 active tracks. This means, the proposed ALE requires only four optical sensors, and it is able to obtain a coded length of 153600mm. The active tracks are:

- step track.

This track contains alternate white and black segments each of the length of the elementary step, 40mm. The step track is used to check the readings from other active tracks.

- fine resolution track.

The track contains fine segments of 0.5mm, alternately white and black. These fine segments are used to measure the elementary step and the mini-steps.

- mini-steps length codifications track.

On this track, the consecutive mini-steps are alternately white and black

- mini-steps binary codification track.

On this track the mini-steps are binary coded, white for logic 1 (A,B,C,D,E) and black for logic 0 (a,b,c,d,e).

The coded strip for two consecutive steps, the step aBCED and the step aBCEd are shown in Fig.3. The conventional binary logic in this optical application is black for logic 0 and white for logic 1. With these observations it is simple to identify the active tracks. The upper track in Fig.3 is the step track. The next one is the mini-steps length coding track, followed by the mini-step binary coding track. Finally, the lowest track is the fine resolution track.

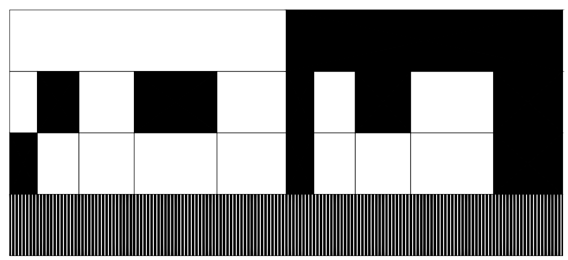

Fig.3. The coded strip for two consecutive steps

Each active track is read by an optical sensor. The number of optical sensors for the proposed ALE is four. Thus the proposed ALE provides an economical solution for long distance applications. The output signals of the entire optical sensor for the steps presented above are shown in Fig.4.

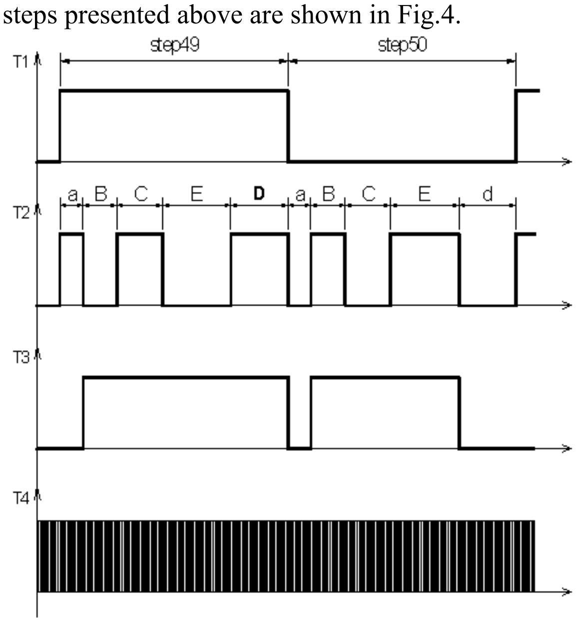

Fig.4. The signals from the optical sensors

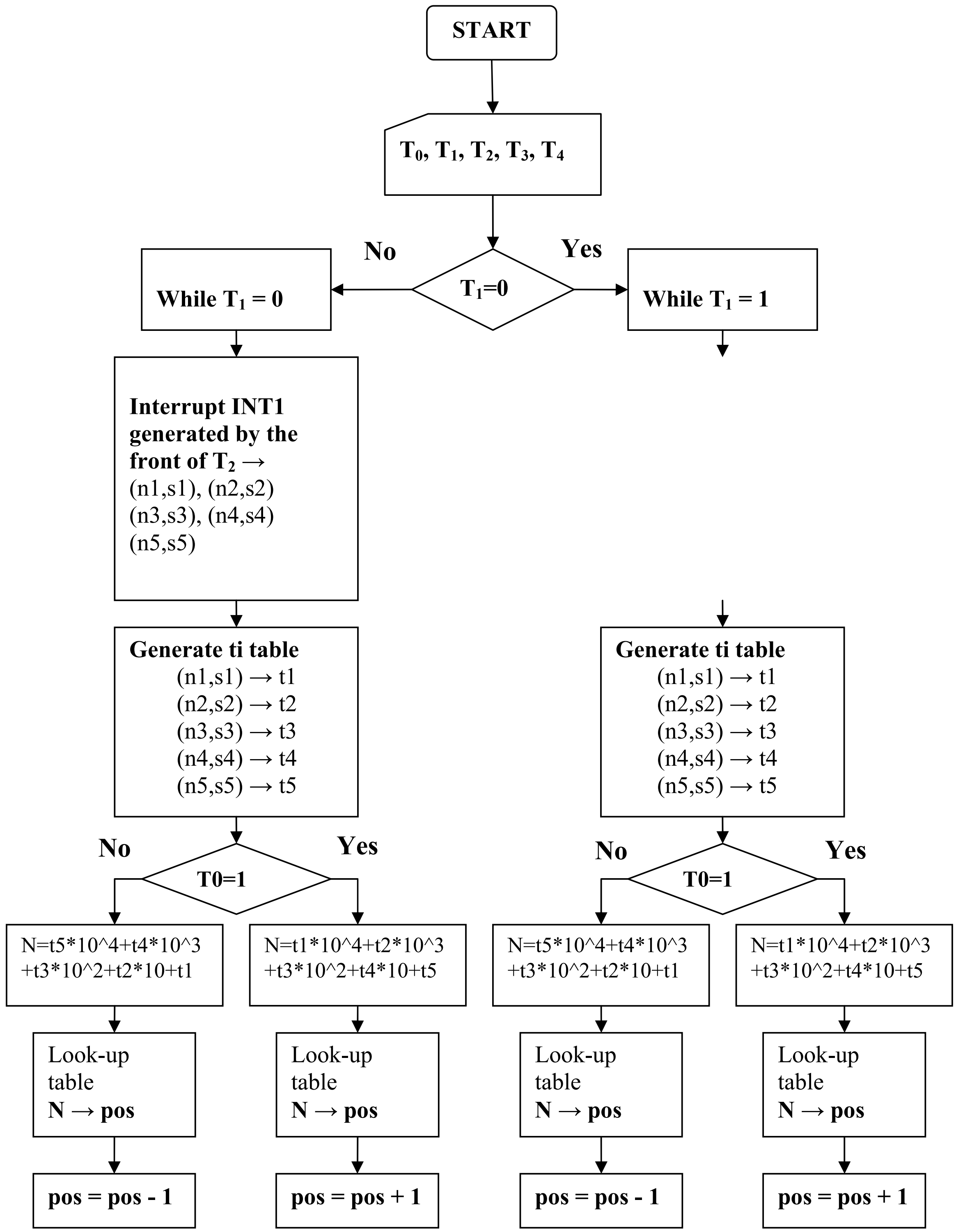

Fig5. Flowchart of the optical device

All signals from the set of optical sensors are digital signals. The correlation between the signals from the mini-steps length coding track and the fine resolution track determine the numerical value of the mini-step length. The correlation between the signals from the mini-steps length coding track and the mini-steps binary coding track offer the variables A or a, B or b…E or e. Using these observations, the dedicated software creates a new numerical coding:
a=0, b=1, c=2, d=3, e=4
A=5, B=6, C=7, D=8, E=9
This new code may be implemented using the following logic pseudo-algorithm:
IF the count of fine resolution impulses during a mini-step is 8 and the mini-step sign is 0
THEN a becomes 0
IF the count of fine resolution impulses during a mini-step is 12 and the mini-step sign is 0
THEN b becomes 1
IF the count of fine resolution impulses during a mini-step is 16 and the mini-step sign is 0
THEN c becomes 2
IF the count of fine resolution impulses during a mini-step is 20 and the mini-step sign is 0
THEN d becomes 3
IF the count of fine resolution impulses during a mini-step is 24 and the mini-step sign is 0
THEN e becomes 4
…………………..
IF the count of fine resolution impulses during a mini-step is 24 and the mini-step sign is 1
THEN E becomes 9

For all 43200 steps, the new code becomes:
{98765} {98760} {98715} {98710} {98265}
{98260} {98215} {98210} {93765} {93760}
{93715} {93710} {93265} {93260} {93215}......
{06289} {06284} {06239} {06234} {01789}
{01784} {01739} {01734} {01289} {01284}
{01239} {01234}
This numerical coding provides the correspondence between the absolute positions of the moving part and all the sets of 5 decimal numbers (the code).
Fig.5 shows the flowchart of the dedicated software. The input signals are the signals of the optical sensors:
- T_o is the direction signal (1 for positive direction and 0 for negative direction)
- T_1 is the step signal
- T_2 is the mini-step length coding signal
- T_3 is the mini-step binary coding signal
- T_4 is the fine resolution signal
- n1, n2, n3, n4, n5 - describe the length of the mini-steps
- s1, s2, s3, s4, s5 - describe the binary coding of the mini-steps
- t1, t2, t3, t4, t5 - the decimal coding of the data pairs (n1,s1), (n2,s2) (n3,s3), (n4,s4) (n5,s5)

3 The optimized version of the ALE

Optimization of the design of the proposed ALE required consideration of some imposed specifications: the optimized version must conserve the coding method, the number of optical sensors used, the number of active tracks, and the principle of numerical coding of the steps. The objectives of the optimization are to double the coded measurement range of the ALE (from 172800mm to 345600mm) and to reduce discrimination (from 0.5mm to 0.25mm). To obtain this performance the coding algorithm must be improved and some parts of the software will change. The essential element in the optimized design is the new task of the step track. Initially, the step track offers the possibility to obtain information about the size of the current step and provides a check on the readings from other active tracks. If the step track is used in the coding algorithm it is possible to improve the coded distance performance of the ALE.
Starting from these considerations, the step track is also used also in the coding algorithm. In this case, the mini-steps track binary coding will be changed. The first variant of the coded strip contains the consecutive steps:
{A,B,C,D,E}{A,B,C,D,e}{A,B,C,d,E},{A,B,C,d,e},{A,B,c,D,E},…,{a,b,c,D,E},{a,b,c,d,E},{a,b,c,D,e},{a,b,c,d,e}………….
If the step track is used in the coding algorithm, the mini-steps binary coding track contains consecutive double steps:
{A,B,C,D,E}{A,B,C,D,E}{A,B,C,D,e}{A,B,C,D,e}{A,B,C,d,E},{A,B,C,d,E},{A,B,C,d,e},{A,B,C,d,e},{A,B,c,D,E},{A,B,c,D,E}…{a,b,c,D,E},{a,b,c,D,E}{a,b,c,d,E},{a,b,c,d,E},{a,b,c,D,e},{a,b,c,D,e},{a,b,c,d,e}{a,b,c,d,e}………….
Also, the mini-steps length coding track contains consecutive double steps.
In this way the available number of coded steps becomes $120\times 32\times 2 = 3840\times 2 = 7680$
and the maximum coded length is
$76800\times 40 = 307200mm$.
The disparity between two identical steps is determined by the binary information from the step track. Consider a pair of steps {a,B,c,D,e}, {a,B,c,D,e}. For the first one the additional binary value from the step track is 0 and for the second, the additional binary value from the step track is 1:

{0,a,B,c,D,e}, {1,a,B,c,D,e}. These additional binary values will be attached to the numerical coding of the steps, in the position of MSB (most significant bit).
Fig.6. shows the new coded strip for two consecutive steps {0aBCDE} and {1aBCDE}.

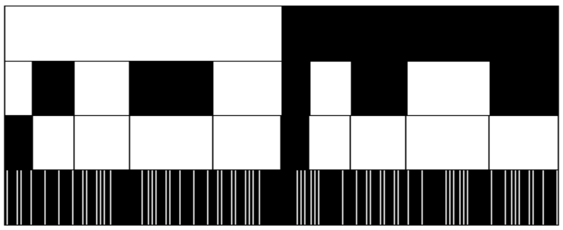

Fig.6. The new coded strip of the optimized design

An improvement in discrimination is obtained by using the rising edge and the falling edge of the fine resolution track signals. The first ALE counted only the impulses of the fine resolution track sensor. For this reason the discrimination was fixed by the length of the track segments (0.5mm). Fig.7 shows the principle of the closer discrimination measurement:

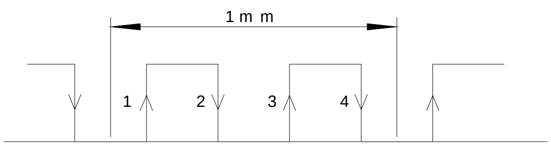

Fig.7 Principle of the close discrimination measurement

3.1 Experimental measurements

The experimental arrangement shown in Fig.8 uses a rotary trajectory instead of a linear one. This makes the test method easy and economical. The first set of measurements determines the working limits of the optical sensors: the maximum tracking speed, the maximum distance to the tracks, and maximum angular deviation. Additionally the experimental setup can simulate mechanical noise by using a rugged surface roll.
The proposed ALE is implemented in an economical way, using standard optical sensors (type KEYENCE FD-FM2) and a high performance optical fiber sensor for the fine resolution track only (type KEYENCE FD-G4 with lens FX-MR3), [6]. The distance sensor-coded strip range is 5mm-8mm, the maximum angular deviation is 5°. In these conditions the maximum working frequency of the fiber optic sensors is 4000 Hz (for surfaces, both smooth and rugged). This maximum frequency determines the maximum speed of the moving part to be 2m/s.

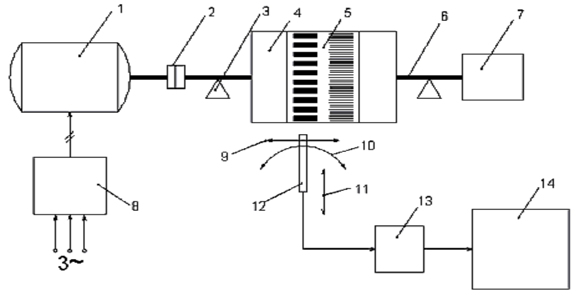

Fig.8 Experimental arrangement
1. DC electric motor; 2. disc clutch; 3. bearings; 4. roll; 5. coded strip; 6. shaft; 7. speed transducer; 8. inverter; 9. distance adjuster; 10. angle adjuster; 11. distance adjuster; 12. optical fiber sensor; 13. optical amplifier 14. data acquisition system

4 Conclusion

A new concept of absolute linear encoder optimized for measuring long distances, suitable for use in intelligent transportation systems, has been proposed and has been validated by experiment. The major benefit is the small number of optical sensors and active tracks. Only four sensors and four active tracks are necessary to encode the distance of 307200mm with the 0.25mm discrimination, in the optimized design. The new encoder is a robust solution, able to work in a noisy environment. The maximum speed of the moving part (the vehicle) is 2m/s.

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