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# DEVELOPMENT OF AN INDEX TABLE FOR MACHINE TOOLS

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***Abstract.*** *Index tables are devices used in machine tools for the manufacture of parts, reducing machining time for some profiles and maximizing the geometric accuracy. Index tables are a variation of the dividing heads, widely used in conventional milling. The machining of cylindrical profile through a Cartesian coordinate system can not produce a highly accurate product due to constructive aspect of the machine itself. The reflection of the need to reverse this situation is the implementation of rotational axis in machine tools. Be in the piece fixing or cutting tool inclination, the inclusion of rotational axis beyond the linear axis increase the performance of machining of machine tools. This paper deals with the design and development of an index table of low cost, high accuracy, and can be used on CNC machines, measuring by coordinated and conventional machine tools.*

***Keywords:*** *index table, accuracy, machine tool…*

## 1. INTRODUCTION

The development of machines has fueled the significantly machine tool market, and increasing the accuracy by these machines is a common point.

In 2010, there was a sharp decrease in global production and consumption of machine tools, but in 2011 the trade situation has returned to grow, according to the website of Gardner (2014). In 2009 there was a peak in sales of about 68 billion US dollars, and 2009 and 2012 was the peak of production, both around 78 billion US dollars. This very promising market serves as motivation to numerous studies, both improvements in already commonly used as the creation of new devices.

Traditional machining centers are carriers of three linear axis, however, is becoming more common the commercialization of 1 or 2 additional rotational axis. Studies have shown that the addition of these rotational axis can be an additional sources of error, mainly due to the dynamic imbalance that might be caused by the additional structure.

Index tables, or rotating tables, are devices used in machine tools (machining centers) in the manufacture of parts, in order to achieve greater geometric accuracy of profiles. Index tables are a variation of universal dividing heads, widely used in conventional milling in manufacture of gears, drilling flanges and circular tears.

The operation of the universal dividing heads is calculated according to the desired angle value, so you can use a splitter disc with the correct number for the equivalent fraction. The construction of an index table is generally a spindle and a disk provided with blades with a simplification of the principle of a universal dividind head (screw worm and crown).

The cylindrical machining profiles through a cartesian coordinate system don't produces a high precision product due to the constructive aspect of the machine itself. The manufacturers of these machines separately provide the rotational axis in addition to the upgrade of the CNC control program, sometimes this could be expensive.

According to Liu (2005), the precision of the machining process has attracted the attention of many researchers. The research covered more in machine tools is focused on clearing mistakes and mapping of the sources of these errors, Ramesh (2000). Kakino (1987) made a study that can find the origin of errors. This and others studies has been used by another scientists to analize and create parameters to development of new devices and performance:

- Kiridena&Ferreira (1993) - developed a general kinematic model of a machine tool;
- Suh (1998) - presented a complete modeling for rotary tables;
- Srivastava (1995) - used the Denavit-Hartenberg (DH) parameters to create a mathematical model of volumetric error;

- Ibaraki (2013) - developed the simultaneously test methodology for rotary axis (A' and C') of 5-axis machining centers;
- Lei (2007) - developed a triggering test simultaneously just the two rotary axis;
- Lei (2014) - conducted a generic test to observe the behavior of each rotary shafts combined with each linear axis;
- Hong (1997) - test method using a bar and a tip-dimensional tests;
- Knapp (1983) - test method using a disk and a tip of two-dimensional tests;
- Brian (1982) - method using a double ballbar to measure the distance between the bases during the circular movement of the shafts;
- Chen (2014) - analysis using ballbar to detect circular profile generated by each combination of rotary and linear axis;
- Qiu (2001) - connected two bars and two encoders at the ends of the linear axis of the machine to detecting the rotation angles of the each axis instantly;
- Heidenhain (2002) - KGM circular test system, consisting of a mesh of encoders and sensors arranged on a disc, in order to obtain accuracy of the system dynamically;
- Kunzmann (2005) - the geometric accuracy of the workpiece can be feeding back metrologically achieved by a closed loop system;
- Schwenke (2008) - improved the study Sartori&Zhang (1995) to compensate the numerical error and methods for measuring geometrical errors of an index table.

In this line, can be developed a simple index table, inexpensive, electronically controlled, high-precision, both for computer numerical control machines (CNC), as for conventional machines and coordinated measuring machines (CMM).

## 2. DEVELOPMENT OF AN INDEX TABLE FOR MACHINE TOOLS

Conventional machining processes is common to use dividers heads at the machining of elements in angular division of parts such as gear teeth, external squares and drilling flanges. Repetitive handling of this equipment at the time of preparation of these divisions has inspired the creation of a device that automates this placement service for manufacture these parts, making it the goal of this work. Figure 1 illustrates an index table (in section) and a universal dividing head.

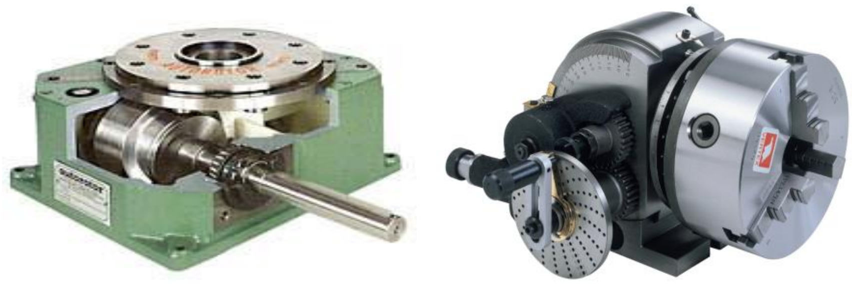

Figure 1. Index table and universal dividing head.

### 2.1 Mechanical Development

The found way to automate this process requires the addition of a data input interface by the operator and an electronic circuit capable of driving an electric motor. The developed system, Figure 2, is based on the universal dividing heads, which use a system coupled with a worm shaft and a ring gear, and between the motor and the worm screw, a gears train is installed to providing a primary reduction. The primary reduction can be adjusted by the operator replacing a couple gears, i.e., the reduction is interchangeable.

Description of machine parts:

1. Bases - upper and lower;
2. Space bars;
3. Right side plate (bearing the train bearing gears);
4. Left side plate;
5. Worm shaft with gear;
6. Radial screw-nut;
7. Intermediate Plate (bearing the train bearing gears);

A. Central shaft with ring gear;
B. Gears train.

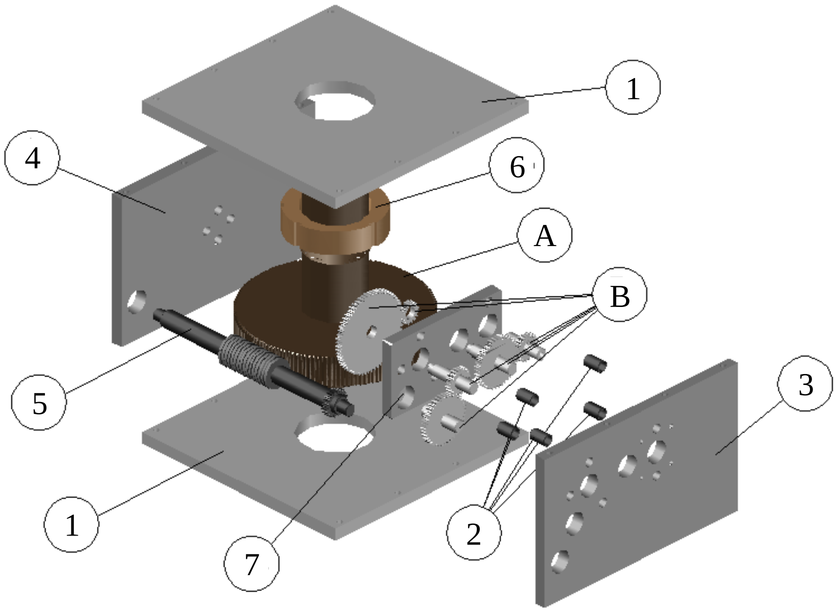


Figure 2. Mechanical parts designed using a CAD software.

The transmission calculus has used a traditional example: the making of a gear with 127 teeth. This is a common problem due to the lack of the disks with a series of 127 holes, or multiples thereof, besides the large number of teeth becomes repetitive work.

The angle generated in the movement of the divider head will be exactly the value of the angle between the teeth of a gear, given by Eq. (1), (SENAI, 2003), and illustrated in Fig. 3:

$$\theta = \frac{360°}{Z} => \frac{360°}{127} => \theta = 2{,}83° \tag{1}$$

, where: $\theta$ = angle between teeths
Z = teeth's number

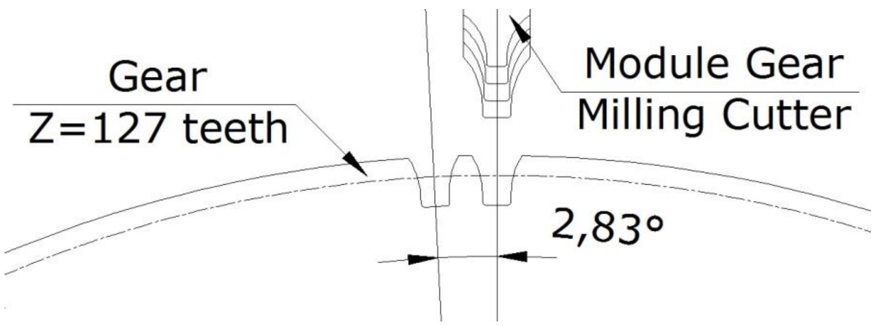


Figure 3. The angle between the 127 teeth of a gear.

The estimated response of the system, take this practical example, where the milling does not always have a dividing disc capable of performing such an operation, which requires adaptations and additional calculations as well as the overwhelming task of repeating the positioning tool 126 times after the first cut. Assuming that the machine has a divider disc with the series of 127 holes, the calculation can be performed according to Eq. (2), cited by SENAI (2003).

$$Div = \frac{P_{cab}}{Z} => \frac{40}{127} \tag{2}$$

ie, 40 holes at series with 127.

, where: Div = turns on universal dividing head
$P_{cab}$ = twist of universal dividing head, usually equal to 40
Z = teeth's number to be manufacture

The rotation of 40 holes in the series with 127 of universal dividing head entry will generate a turn of 2,83º in the output, ie, each hole of dividing head will provide a movement of 255,12”. If the operator commit a mistake of adding or decreasing one hole, the error at geometric tooth profile is equal to 255 seconds arches, approximately.

From this value, we can establish initial parameter as a value for the resolution of the automated system division (automated index table).

*A priori*, it was estimated a value ten times smaller than the 255 seconds arches. However, with the commercially available kit and tools in making the prototype, was designed a system with a resolution approximately 89 seconds arches, near 3 times lower than the 255 arches.

The prototype were designed and developed in CAD software, observing the norms of adjustments and tolerances necessary for smooth operation and total engagement of the parts. The gears train accomplishes a reduction in the movement of 9 times, which in turn is reduced by 145 times the worm and crown assembly, ie, the total gear ratio of the system is 1,305 times.

But, for preliminar tests the gears train will not accomplishes a reduction, will only be connected to the motor a gear of 40 teeth which transmit the movement to the gear of 20 teeth the worm shaft. According to Eq . 3 (Shigley, 2004):

$$e = \frac{Z_1}{Z_2} * \frac{Z_3}{Z_4} * \ldots * \frac{Z_{i-1}}{Z_i} => \frac{Z_1}{Z_2} * \frac{Z_3}{Z_4} => \frac{40}{20} * \frac{1}{145} => e = \frac{1}{72{,}5} \quad (3)$$

, where: e = transmission ratio

$Z_{odd}$ = motor teeths

$Z_{even}$ = follow teeths

i = total of used gears

The structure were made with AISI 1020 steel, all gears and shafts were made with aluminum, beyond bearings and a step motor (1.8°) was adopted.

The pulse stepper motor drive will provide a movement into the system with 6.480 second arcs (1.8°), and output motion being 72.5 times smaller than the input motion, this will turn the output shaft approximately 89 seconds arches. Once the mechanical assembly is designed, it remains perform an electronic control of the input movement to achieve a better resolution.

## 2.2 Electrical Development

The system control will be held in closed loop, feeding back the position of the motor shaft through an encoder. Encoders are equipment used in all branches covered by industrial automation, mainly because it is easily adaptable to the mechanisms of the machines, maintenance simple and cost-effective, Fig. 4.

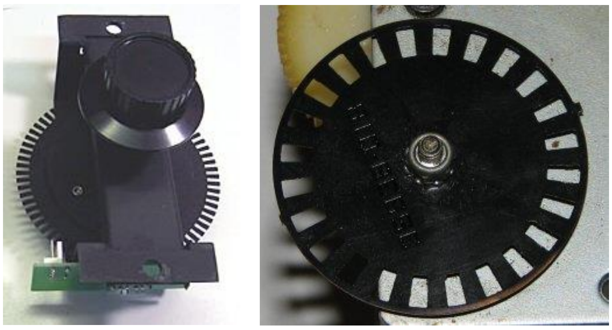

Figure 4. Encoders examples.

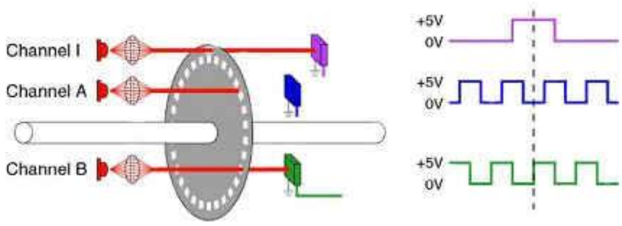


Figure 5. Encoder and wave form.

A source emits a light (phototransistor) directed to the holes at the disk, Fig. 4, and on the other side of the disc there is a photoreceptor member. At the moment of the disc interferes with the passage of light, e-PR circuit emits a low level digital signal. But the instant the disc allows the passage of light, the electronic circuit PR issue a digital signal high level, as illustrated in Fig. 5. Thus, the light emitted by the phototransistor is "discretized" the disc, making the PR submit a pulsating electrical signal due to the pulsing signal light received.

In this paper, the digital signal sent from the encoder will be greeted by a circuit board, known as ARDUINO, which will play the role of system controller. The ARDUINO has interface with personal computers (PCs) via a USB port, facilitating communication, faster than serial ports. The USB port is increasingly replacing serial ports, which in turn, serial ports are also extinct in notebooks (which included only in exceptional requests). The programming of these plates are in the C ++ language, known and widespread in the communities of professionals in the areas of control and automation.

"Arduino is a project that includes software and hardware designed to provide an easy platform for prototyping interactive projects using a microcontroller. It is part of what we call physical computing: physical computer area in which the software interacts directly with the hardware, enabling easy integration with sensors, motors and other electronic devices "(Justen, 2014).

The ARDUINO illustrated in Figure 6 is the version UNO - an Italian version of Duemilanove, 2009, which is widely marketed today. Has a very satisfactory configuration for small projects, clocked at 16MHz, memory 2kB RAM, 32kB of flash memory, 14 digital ports and 6 analog inputs.

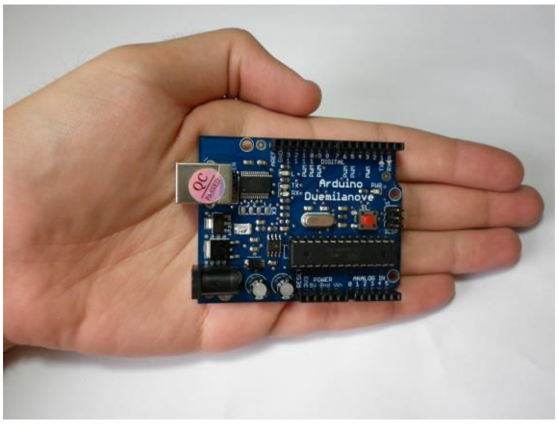


Figure 6. ARDUINO UNO (basic board version).

The characteristics of the UNO version is attractive for small projects and for an initiation into the world of physical computing, an area that has become increasingly higher, reflecting the emergence of small controllers. The ARDUINO’s board is smaller than the palm of a hand, friendly interface with the PC, price accessible and with great developer's advantage no longer need to build your own controller.

The ARDUINO software is free and available to download on internet with ready libraries of mathematical functions, counters, timers, and other drivers. One of these drivers is the EASYDRIVER board control, Fig. 7, this board can control DC motors (DC) and step motors. In the case of DC motors, this board acts as an H bridge to drive two motors, clockwise and counterclockwise. In the case of step motors, this board can control just one motor, receiving the pulses emitted by the controller to clock and direction of rotation, and thus the board already emits respective signals of each of the 4 stepper motor coils.

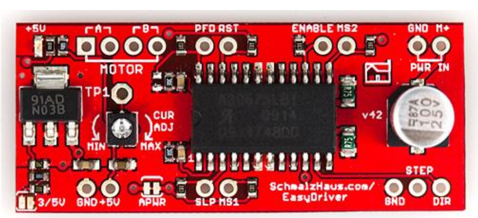


Figure 7. EASYDRIVER board.

In this project, the ARDUINO will connect push buttons, encoder, interface screens and EASYDRIVER boards for control of stepper motors. When pressing one of the push buttons, the stepper motor will receive the number of pulses corresponding to the degree required in the interface screen. The encoder will tell the displacement controller, which will verify that the stepper motor acted correctly, and otherwise, the controller will make the correction placement.

In programming EASYDRIVER board it's possible to make subdivisions to pulses of the stepper motor, to reduce the "factory step."As mentioned above, the "factory step" of the motor used is 1.8 ° and the reduction of motion adopted by the gear ratio is 72.5, thus obtaining an offset at the output shaft around 89" for each normal stepping motor. The EASYDRIVER board reduces the input rotation 8 times, thereby maximizing the resolution of the index table for something about 11".

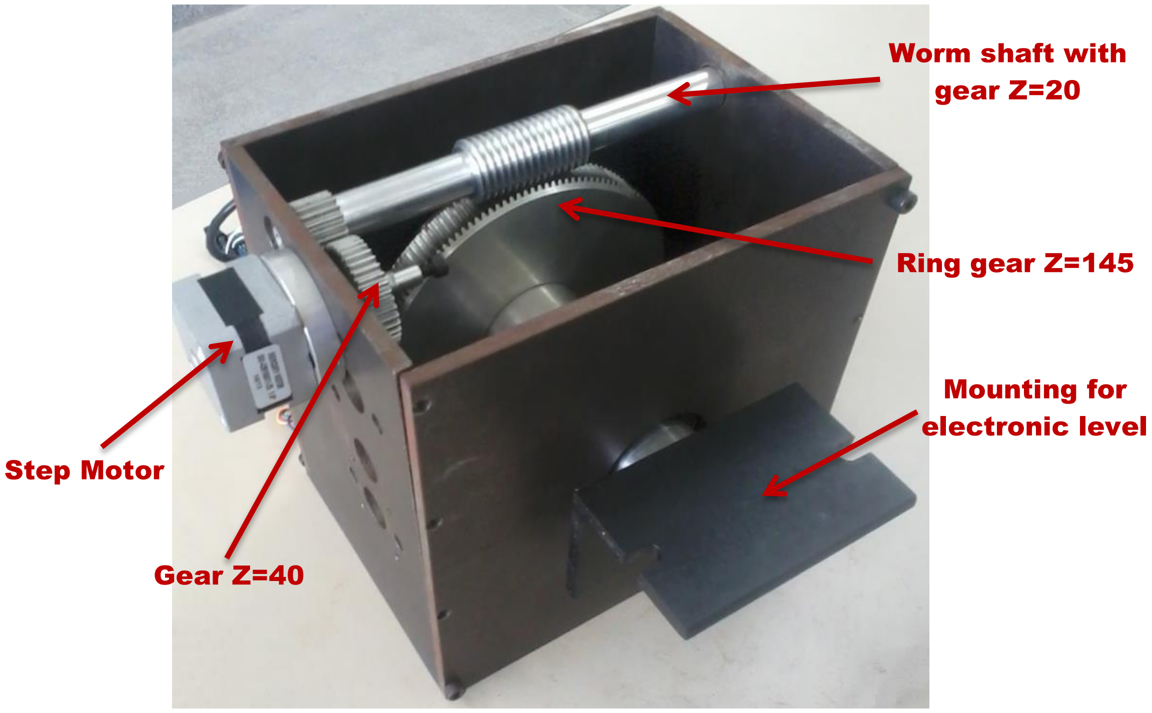


Figure 8. Prototype ready for preliminary testing and adjustment.

## 3. TESTING PROCEDURES AND PRELIMINAR RESULTS

For the initial programming of tests and adjustments made elements, the control of prototype was carried out in opened loop. The Figure 8 show the input shaft without encoder.

The testing procedures will obey the following sequence:

- step motor receives 10 pulses with "factory step" (1,8º), thirty times in clockwise;
- step motor receives 10 pulses with "factory step" (1,8º), thirty times in counterclockwise;
- step motor receives 10 pulses with reduced step (1,8º/8), thirty times in clockwise;
- step motor receives 10 pulses with reduced step (1,8º/8), thirty times in counterclockwise;

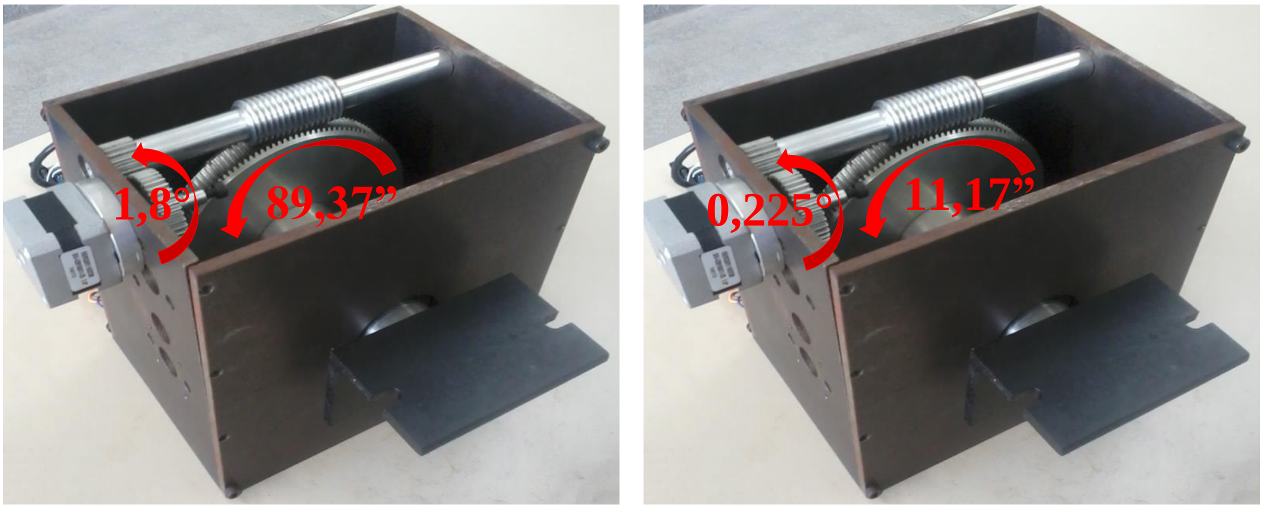


Figure 9. Illustration of the methodology used in preliminary testing.

Each normal engine step should generate a displacement of 89.37", so 10 pulses to stepper motor then should the output motion is equal to 893.7" in clockwise and counterclockwise. Subsequently, using the feature of EASYDRIVER board was also sent to the stepper motor 10 pulses with 1/8 normal step should produce a movement on the output shaft of 111.7" amplitude in the clockwise and counterclockwise.

Altough the prototype be able to perform complete rotations, the tests were done in only a certain range, due to the limitations of the electronic level. The measuring instrument adopted for the tests was an electronic level of Taylor Hobson, Talyvel 5 model, this instrument has a resolution of 0.1", and measuring range of -600.0" to +600.0" (spam = 1,200").

The electronic level was fixed to a mounting fixed on the output shaft of the ring gear, thus the prototype was positioned at an angle close to the lower limit of the measurement range of the electronic level. After positioning and withdrawal of mechanical clearance, the prototype is started for testing at the lower limit of rotation to the upper limit. After this procedure, the tests continued in reverse direction.

Applying the metrology concepts, Junior (2008), for: average (Eq. (4)), tendencies (Eq. (5)), error (Eq. (6)), standard uncertainty (Eq. (7)), and expanded uncertainty (Eq. (8)) trend to validate the results obtained in preliminary tests of the prototype as a type system "black box", ie, the average value is equal to the tendecy, we come to the data presented in Tab. 1.

$$\bar{I} = \frac{\sum I}{n} \tag{4}$$

$$Td = \bar{I} - RV \tag{5}$$

$$E = I - RV \tag{6}$$

$$u(I) = \sqrt{\frac{\sum_{k=1}^{n}(I_k - \bar{I})^2}{n-1}} \tag{7}$$

$$cS = u(I) * 2{,}7574, \text{ for 99\% assurance} \tag{8}$$

, where: I = measurement value

$\bar{I}$ = average measurement value

n = number of measurements

RV = reference value

Td = tendency

E = error

u(I) = standard uncertainty

cS = Student coefficient

Table 1. Results of preliminary tests with opened loop system.

| **10 PULSES** | **AVERAGE VALUES ACCORDING TO THE DIRECTION ROTATION (second arcs values)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | CW | Tendency | u(I) | cS | CCW | Tendency | u(I) | cS |
| Factory | 904,31 | 0,00 | 11,69 | 32,23 | 904,00 | 0,00 | 11,53 | 31,79 |
| Reduced | 100,41 | 0,00 | 2,25 | 6,21 | 100,21 | 0,00 | 2,12 | 5,86 |

## 4. CONCLUSIONS

The results presented in preliminary tests showed very encouraging values. Even the prototype working in opened loop, the system response was very close to the estimated value, which implicitly shows that the first stages of machining and assembly were well projected and executed.

According to Table 1, we can report that the prototype mounted preliminarily has a reliability of their position greater than 40 times the higher uncertainty produced (expanded uncertainty at clockwise rotation) by the passage of a hole divider head mentioned earlier in this article (255.12"/6.21" = 41.08x).

The next step is to create an independent interface for rotation adjustment, installation of an encoder to close the control loop and machining the gear train to increase the resolution of the system. After this step, we test for the verification of geometric errors and system reliability with type measuring instruments: electronic level, dial gauge and ballbar.

The next gears train will be able to high the index table resolution near to 0,62" and the prototype don't need be connected to an PC, ie, more precision, easy interface, portable and self-contained.

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