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PROPOSAL OF UNIVERSAL COMMUNICATION SYSTEM FOR SERVICE ROBOTS

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Keywords: service robot, wireless control, teleoperator
Abstract: Area of service robotics is characterized by increasing amount of device which is defined to perform various tasks. In most of cases the service robots are controlled remotely from an operations centre at performing their tasks. In order to control robot an operator has available special drivers or software on computer that allows the control of only certain devices. This article deals with the design of the communication channel, which will be used as the basis for creating a universal tool for remote control of service robots of various kinds. This article focuses on the description of the data structures needed for the transmission of specific data in two-way communication.

1 Introduction

Area of service robotics is characterized by increasing amount of device which is defined to perform various tasks. In most of cases the service robots are controlled remotely from an operations centre at performing their tasks. In order to control robot an operator has available special drivers or software on computer that allows the control of only certain devices.

This approach is suitable for commercial use, where the customer gets tools for remote control (either computer software or special drivers) of bought robots. In a process of development of prototypes of service robots that have different design principles, it is appropriate to create a universal system of wireless communication that it could be implemented into the any of developed robotic devices.

The creation and subsequent use of universal communication system for service robots brings several advantages such as:

- decreasing of needed time for the phase of development
- the possibility to control several robotic devices in the same time by the use of the universal control tool
- the possibility of easy implementation onto devices of OS windows or OS Android

2 Description of the communication module

For the purpose of ensuring a bi-directional wireless communication channel between an operator and service robots is necessary to select the appropriate radio frequency. The radio communication is managed by strict rules today to avoid unwanted interference with other devices. For research and development purposes should be used worldwide-free bands ISM 2.4 GHz corresponding to the IEEE 802.15.4 standard.

There are many devices that can be used to create a wireless communication. Therefore it is very important to determine the basic requirements for given device such as a distance between an operator and a device, the way of communication between the MCU and a wireless communication module, required transmission rate, the maximum size of the transmitted data and other.

Area of application of developed service devices is a combination of indoor and outdoor applications. For Outdoor applications is supposed a maximum distance between the robot and the operator of 1000m. This condition is derived from the legislative amendments for common drones to 20kg. The reason is the assumption of implementation of robotic flying devices that belong to the group of drones. The use of terrestrial or floating devices isn't legislative regulated in any way, so the maximum distance at which it is possible to remotely control robots derived from a group of drones to 20kg. The operation of drones to 20kg is not yet subject to a license from the Transport Office.

Selected module nRF24L01p Nordic Semiconductor that includes a power amplifier (PA) and low noise amplifier (LNA) allows you to create a stable communication channel capable of communication over long distances. In the open area by using antennas with gain and 2 dB selected data rate of 250 kbps it is possible to transmit information about a distance of 1300 meters. This distance is fully suitable for the intended type of application. More characteristic information's about the communication module nRF24L01p is shown in the following table (Table 1).

Table 1 nRF24L01p specifications

Maximum output power	+20 dBm
Maximum Payload	32 bytes
Communication with MPU	SPI (8Mbps)
Sensitivity 250kbps (received)	-104 dBm
PA gain	20 dB
LNA gain	10 dB
LNA Noise figure	2.6 dB
Antenna Gain (peak)	2 dB
2MB rate (Open area)	520 meter
1MB rate (Open area)	750 meter
250Kb rate (Open area)	>1000 meter

3 Description of a data frames

The main purpose of the proposal of communication channel is to acquire a versatile tool for remote service robots with one unit (Figure 1). In addition to the control signals it will can to obtain status information of a given robotic devices. Also the proposal of the communication channel will be create the basis for creating apps for PC (Windows) and mobile platforms (Android).

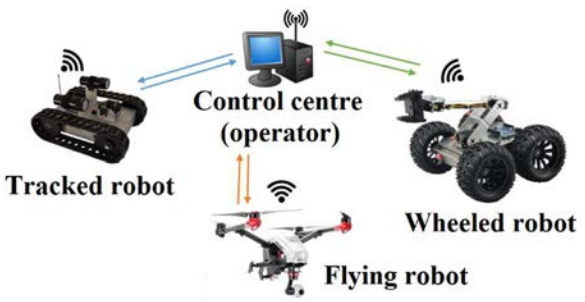

Figure 1 Scheme of control of different kind robots

The basic proposal of communication channel is created for control of movement of three basic types of service robot - for terrestrial service robots with differential control, for terrestrial service robots with controlled axle and for flying robots. The reason for choosing this group of service robots is the fact that the majority of implemented service robots can be classified into one of these groups.

Significant representation in practice has a group of terrestrial robots. The fundamental data for a controlling of the robot movement are data about speed and direction. We can mark these basic movement data as a "motion a frame".

For determine the movement forward and backward we can use only one bit of this frame. That means if this bit will have a value of 0, the robot will perform a movement forward and vice versa. For purpose of speed control is need to use bulkier information. In order to smoothly and accurately control a speed of movement it's necessary to use information about 10 bits of a motion data frame. In theory by this way it will be possible to control a speed of robot by using 1023 levels. In practice it will not be possible because the engine at low levels will not start. This fact we have to keep in mind when we are programmer, but for common users is this information irrelevant because the software adjustment removes this state.

Another 10 bits we will use to control direction to the right or to the left. There is no need to use the all 10 bits to identify turning in each direction separately. It's usefull divide the range of 10 bits into two parts. The zero bit of the frame we will use to control of a direction. If the zero bit will have value 0 a robot will turn in to the left and vice versa. The remaining 9 bit will control radius of turning.

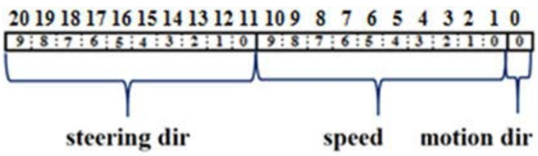

Figure 2 21 bit motion frame of terrestrial robot

Into the area of service robotics penetrate increasingly unusual flying device - drones. Control principle of these devices is very simple but very different in compare to terrestrial robots. It is therefore necessary to use a different data format, which will transmit the necessary information for their management. Because no matter how much has multicopter rotors can be used for all these facilities the same data format.

The most important data is information about the performance of motors. By these data is regulated the flight altitude. Because multicopters use special brushless motors, which have a large speed range which controls the power, it is necessary to have appropriate control range. For the purpose of transmission information about performance we use the 10-bit word. Because a performance of all engines is the same at the moment we can use only one 10 bit data word for regulation of all motors.

Direction of flight and its speed is controlled by a slope and a tilt of the whole frame of a drone. The change of a slope and tilt achieve by changing the speed of the engines on the basis of information on the slope and tilt of the IMU. The actual flight control is the responsibility of the flight controller. Its needs to send to control centre only information about where and how fast a drone moves.

Sideways movement of a drone can be described by the X-Y plane. Drone is the middle of grid system. OS X is identical with the direction of movement back and forth and Z axis movement corresponds to movement to the right and left. The resultant direction of movement determined by the angle of the vector which produce components X and Y, and speed in a given direction of its size.

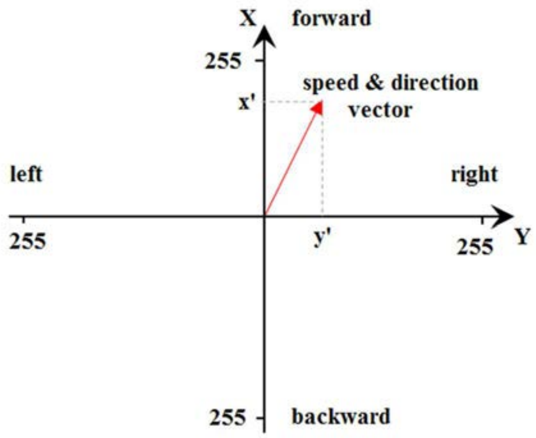

Figure 3 Principle of direction & speed control

For the given principle of control direction and speed of movement, we have to transmit to the control unit information about the direction of flight (2 bits), which is a combination of two bits. Zero bits of the pair tell about the direction of the X axis (1 - forward 0 - backward), the first bit talks about movement in the direction of the axis Y (1 - right, 0 - left). In addition to information about the direction you need to send speed information respectively about tilt in given direction. For this purpose, we will use two 8-bit words. 8-bit word creates range of 256 levels of tilt and slope, which is fully sufficient range to control the direction and speed of flight speed.

For information transfer system designed by this way we need to use a total of only 28-bit word. We can see detailed description and composition on the next picture.

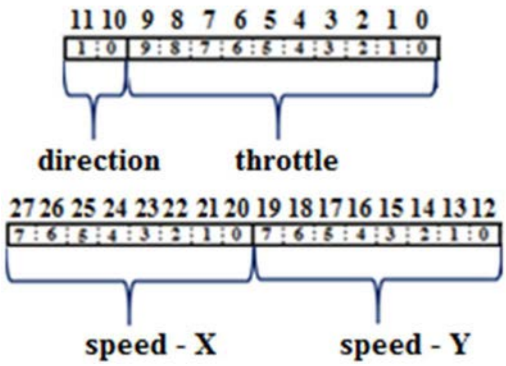

Figure 4 28 bit frame of flying robot

In addition to control information flows, which are directed by the operator to the device, it is necessary to obtain status information of this device. Therefore, it is necessary to create a state information channel. The basic information needed for management includes slope, tilt and orientation of the structure coordinates of GPS and battery status.

It's very important to know the battery charge status for two reasons. The first is a scheduling of operations due to the battery charge level so to prevent battery discharge while performing the task. The second reason is to protect the battery, because today they are commonly used LiPo batteries, which must not be discharged below 2.7V/cell.

The value of the capacity of batteries can be displayed in two ways, by using the percentage display, or by real value in volts. To view by using a percentage display could be used 7-bit word but to see real value in the format DD.d [V] will use 10 bit value.

0-3 bit are used to express the decimal value volt and 4-9 bit is used to express an integer value potential in volts, up to 63 V.

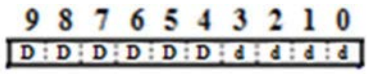

Figure 5 10 bit Baterry charge data frame

For terrestrial and flying robotic devices it is also important to know the actual angle of tilt and its structure. In terms of terrestrial robots it is appropriate to provide this information to the operator in order to optimally control robot and to avoid, for example, to its being overturned. Movement of flying robots, especially drones is based on changing the tilt and inclination. Inclination and tilt is controlled automatically, but it is necessary to know the actual value of the data. Due to the fact that we do not need to use the full 360 degrees and the accuracy of the data will be rounded to the stage, for both slope and inclination data consistency of the data we use the size of 1 byte.

A information that we have to send extra to operator for appropriate control of flying robots is flight altitude. Today, the amount of used altitude sensors achieve high accuracy (± 1 m). Taking into account the maximum wireless range management 1000m legislative regulations, which refer to a maximum altitude of 120 meters, sufficient amount of data to display the current amount is 10 bit

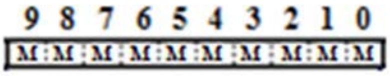

Figure 6 10 bit Altitude data frame

When system is working outdoors will not do without features of tracking of device on basis of the position of the GPS system. To transmit the coordinates we use decimal format DD.ddddd. For the system tracking applicable in all geographical areas, it must also coordinate and transmit information where the device is located. For this purpose we use a pair of bits, and the bit prime position with respect to latitude (0 - North, 1 - South) and the first bit of position relative to the longitude (0 - Eastern, 1 - west).

The actual transmission of the data we use to achieve high accuracy 4 bytes. The first byte will be used to transfer information about the full degrees and the remaining three bytes to transfer six decimal places this number, each byte is divided into upper and lower four bits. Each foursome bits testify about the value of one decimal. That is, the use of three bytes, each of which is divided into two parts, we are able to display just six decimal places. The same data frame we use to describe the latitude and longitude. Overall, for transmitting position data robotic equipment we will use 66 bits.

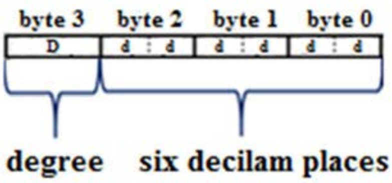

Figure 7 4 byte Longitude/Latitude data frame

Very exact value of slope, tilt and orientation of the frame of the robotic device can be obtained by using Inertial Measurement Units. Accurate figures are necessary for motion control, which is not an internal process to the robot controller and operator to directly interfere in this process. Therefore, controls values, which will be sent to the operations centre can be rounded to integer values of degrees and thus reduce the amount of data transmitted.

We are assuming that the frame of the robot is not rotated in theory more than 90 ° in the direction of the slope, pitch, and may be selected range of ± 90 °. This assumption allows using for data transmission on the slope of only 1 byte and 1 byte as well as the indication of the tilt. Prime and sixth bit of this apartment speaks of an integer value angle and the seventh bit of direction (0 - CW, 1 - CCW). For information on the frame orientation (rotation around the Z axis) we have to use 9 bit information because it uses the full range of 360 °.

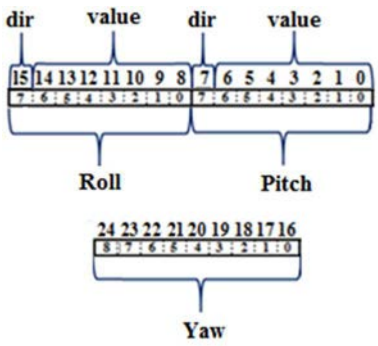

Figure 8 Roll, Pitch and Yaw data frame

Conclusion

The main aim of this article was to propose and describe the universal data communications channel management service robotic devices. Communications channel designed to serve as a basis for creating an application running under Windows Mobile and Android. This application will facilitate and simplify the development and testing of robotic equipment as it relieves developers from design to control communication. Also, the present proposal can be implemented establishment of communication channels already in finished devices, which in turn will be operated together with other devices using the same software.

Acknowledgement
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PRINCIPLES OF MASTERING AT KUKA ROBOTS

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Keywords: KUKA robot, mastering, measurement, SEMD
Abstract: Every robot must be mastered. Only if the robot has been mastered can it move to programmed positions and be moved using Cartesian coordinates. During mastering, the mechanical position and the electronic position of the robot are aligned. For this purpose, the robot is moved to a defined mechanical position, the mastering position. The encoder value for each axis is then saved. The mastering position is similar, but not identical, for all robots. The exact positions may even vary between individual robots of a single robot type.

1 Introduction

Robot mastering is the process of identifying the real geometrical parameters in the kinematic structure of an industrial robot, such as the relative position of joint links in the robot [1]. Calibration is a useful diagnostic method that increases the positioning accuracy of the robotic arm of an industrial robot. Robot calibration is performed to set the correct positions of each robot arm (axis) relative to the base coordinate system. Nowadays, is possible use also ROS mastering for robotics programming as advanced concepts at this area [2]. The method of calibration on different types of robots varies depending on the robot kinematics as well as on the manufacturer's preferences.

Expensive and log calibration methods based on a camera or laser scanning system require specific equipment and accessories, unlike manual calibration, where the financial requirements are minimal, see Fig. 1.

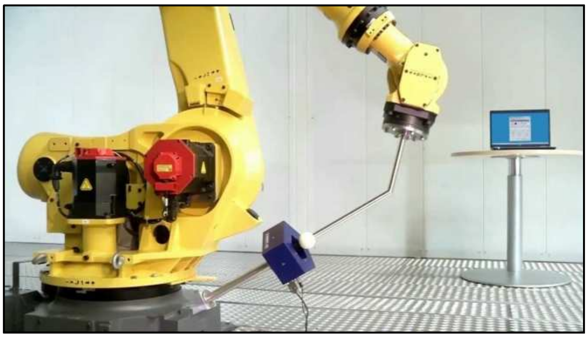

Figure 1 Robot mastering

In practice, it is often used that calibration is most often performed on new robots in production processes [3]. Users, however, want to be sure that machines will achieve required precision after being deployed in the production process. Therefore, it is important to deal with the calibration again after some time.

Regular calibration is very important, because even the best robots tend to lose absolute stability; they show a shift and zero fluctuations, thus losing the ability to accurately position [4]. There are several different calibration methods that are used depending on how many devices to calibrate and what level of precision is required. In some cases, calibration must be carried out directly in operation, otherwise it is appropriate to do it in a workshop or in a calibration laboratory. Consequently, with the help of modern software and camera systems, it is easy to evaluate the calibration result [5].

By calibration we can understand two things. In the first case it is a robot recovery. This process is usually done by the manufacturer as the final step that is necessary for the fully functional product that the manufacturer offers. The revitalization of the robot is based on the unification of individual coordinate systems of robot with their virtual representation, which is stored in the robot's control system [6].

In the second case, the calibration is used to improve positioning accuracy without necessarily or altering of mechanical structure or design of robot. To achieve required positioning accuracy, software that corrects undesirable deviations and optimizes the path is used [7].

Robots, such as mechanical devices, can be affected by minor deviations due to wear of parts, tolerances, manufacturing inaccuracy of spare parts [8]. Calibration reduces the risk of changing the robot program due to these factors. On a general level, the calibration is divided into two groups:

- parametric calibration (kinematics calibration),
- non-parametric calibration (static calibration).

In both cases will be solved following steps:

- model of robot,
- measurement,
- identification,
- compensation or correction.

It should be taken into account the fact that this is a process in which the positioning accuracy of the robot arm is improved by software modification of the positioning [9]. Therefore, it is not necessary to interfere with the robot construction or its control system. This process contains from creation of model that represents real robot at the workplace [10].

Parameters affecting robot precision are precisely defined and measured, see Fig. 2. In next steps, calculated parameter values are inserted into the kinematic model, which exactly corresponds to the actual parameter.

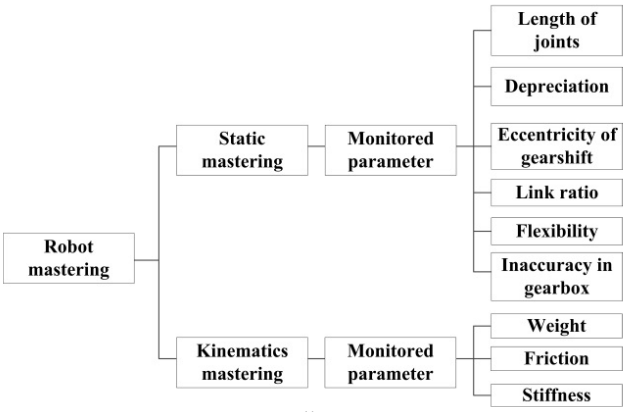

Figure 2 Parameters affecting at robot accuracy

With quick and easy calibration, we can achieve the following benefits:

- If the robot fails, it may be replaced by a new one. Once the calibration has been completed, operation can be restored with minimal downtime.
- Program calibration can be verified at regular intervals. This means that quality is ensured by frequent calibration. Thus savings are a reduction in costs associated with poor quality products.
- Quick calibration also allows you to reduce the insertion or changing of the accessory. Shorter feed-in times then reduce downtime costs.
- Programming is done in such a way that the robot can be replaced without having to reprogram each position.

2 Mastering at KUKA

The calibration method used by KUKA industrial robots uses two types of measuring devices [11]:

- Dial gauge – the calibration is fixed over the measuring tip by means of a thread. Previously, you need to set the help lines to overlap at robot.

By gradually moving of robotic arm at the lowest speed from negative, the measuring tip moves, which can be tracked on the watch handles. When the tip reaches the groove bottom and the hand rises, the measurement is completed [12].

Figure 3 Dial gauge

- SEMD (Standard Electronic Mastering Device) – electronic measurement device – works on a similar principle as a dial gauge, except that it is equipped with a connecting cable to connect the robot with a calibration device [13].

The information from the SEMD device is transferred to the robot where the robot is automatically shut off after the calibration position is reached, see Fig. 4.

Figure 4 Adjusting set with SEMD and MEMD

The thinner cable is the signal cable. It connects the SEMD or MEMD to the mastering box. The thicker cable is the EtherCAT cable. It is connected to the mastering box and to the robot at X32.Description of adjusting set with SEMD and MEMD (Micro Electronic Mastering Device)) can be found in table 1.

Table 1 Describtion of parts in adjusting set

1.	Adjusting box
2.	Screwdriver for MEMD
3.	MEMD
4.	SEMD
5.	Cables

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2.1 Basic setup

Every robot must be mastered. Only if the robot has been mastered can it move to programmed positions and be moved using Cartesian coordinates. During mastering, the mechanical position and the electronic position of the robot are aligned. For this purpose, the robot is moved to a defined mechanical position, the mastering position. The encoder impulse for each axis is evaluated from rotational speed of motor and then saved [14]. The mastering position is similar, but not identical, for all robots, see Fig. 5. The exact positions may even vary between individual robots of a single robot type.

Figure 5 Mastering position – approximate position

A robot must be mastered in the following cases:

- During commissioning,
- After maintenance work during which the robot loses its mastering, e.g. exchange of motor,
- When the robot has been moved without the robot controller (e.g. with the release device),
- After exchanging a gear unit,
- After an impact with an end stop at more than 250 mm/s,
- After a collision.

The axes must be moved to the pre-mastering position before every mastering operation, fig. 6. To do so, each axis is moved so that the mastering marks line up [15].

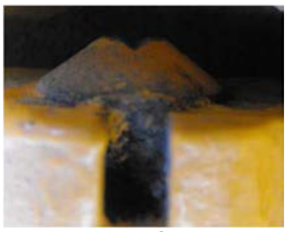

Figure 6 Moving an axis to the pre-mastering position

In some cases it is not possible to align the axes using the mastering marks, e.g. because the marks can no longer be recognized due to fouling. The axes can also be mastered using the probe instead of the mastering marks. The figure 7 shows where on the robot the mastering marks are situated [16].

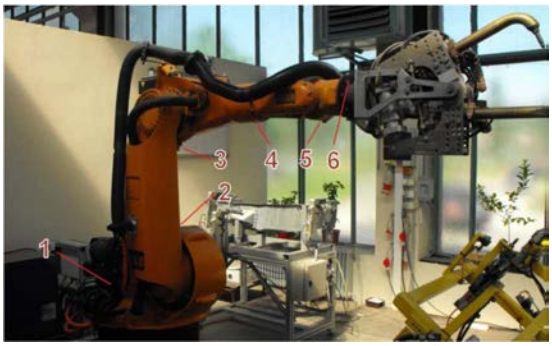

Figure 7 Mastering marks on the robot

To locate the mechanical zero position of a robot axis precisely, it must first be aligned to its pre–mastering position. The protective cap of the gauge cartridge is then removed and a dial gauge, or the supplied SEMD, is fitted to it. The SEMD is now plugged into the robot junction box (connection X32) and thus connected to the robot controller. When, on passing over the reference notch, the gauge pin reaches its lowest point, the mechanical zero position is reached [17].

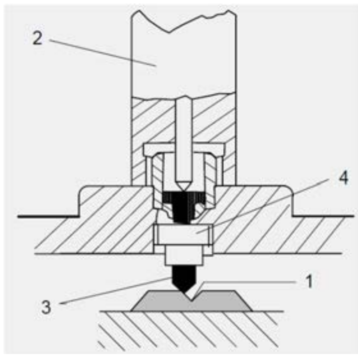

Figure 8 Cross–section of a gauge cartridge

The electronic measuring tool sends an electronic signal to the controller. If using a dial gauge, the zero position can be recognized by the abrupt reversal of the pointer. The pre–mastering position makes it easier to move to the mechanical zero position. The pre–mastering position is indicated externally by a scratch mark or “frontsight/rearsight” markers and is located just before the zero position, see Fig. 9. The robot must be brought into this position before the actual mastering procedure [18].

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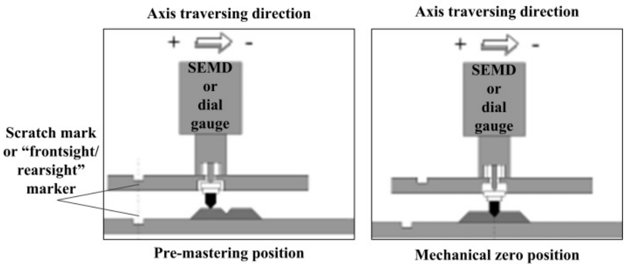

Figure 9 Pre-mastering and mechanical zero position

2.2 Mastering process

A number of different functions are available for mastering with the SEMD. These are grouped together under two main points: "Standard" and "With load correction". The difference here is that using the option "With load correction" it is possible to master the robot as if the tool had been removed, but actually leave the tool mounted on the robot. This is done by correcting the weight of the tool "arithmetically". "Standard" mastering is used if the robot is always mastered with the same tool or always mastered with no tool.

- Removing the protective cap of the gauge cartridge and fit the measuring tool to first axis, fig. 10.

Figure 10 Measurement at first axis

- Connectting the measuring tool to the robot controller using the cable supplied with the EMT set., fig. 11.

Figure 11 Connection cable for EMT

- Preparing the robot for mastering and selecting the menu item "Standard" from the submenu "Set mastering", fig. 12.

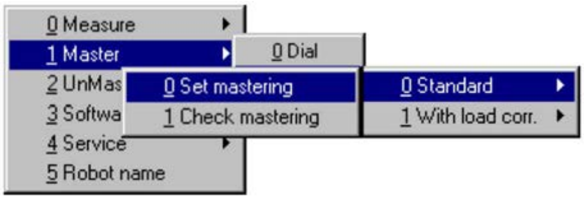

Figure 12 Setting of mastering at Menu

- Oppening of status window (Fig. 13) with describer axis to mastering. The rank of axis for mastering is suited as follows.

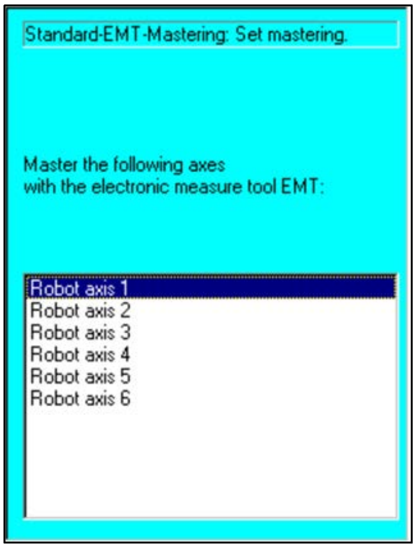

Figure 13 Axis status window

- By pushing of the button for mastering will be setting the first axis. Is necessary to hold "death man" function at the back of the pendant together with green button – start. Blue markered axis will be automatically mastered in direction from + to - .

In case of the finding of deepest point (mechanical zero position) program will automatically stop. Finded values will be stored at memory of robot control system and blue markere axiss will disapear, see fig. 14.

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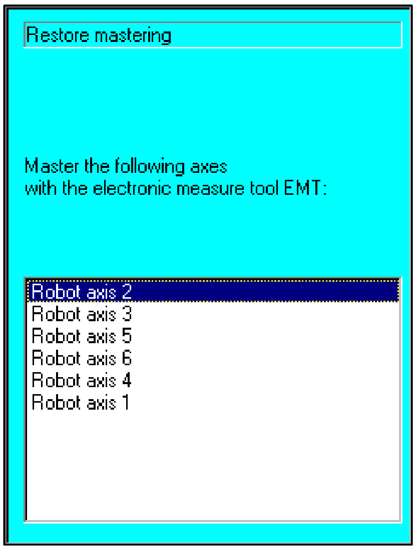

Figure 14 Succesfully mastered first axis

- Repeating the same process at each axis of robot KUKA. If at screen is not displaying any axis, realized mastering was succsesfully.

3 Conclusion

Kinematic calibration can be applied to multiple robots of the same type at the same time. This means that the calibration process is performed once, but is applicable to the robot group. From an economic point of view, kinematic calibration does not require special equipment; on the contrary, static calibration requires special external devices, thus increasing the costs required for static calibration. Constructing of kinematic model requires expert service, unlike static calibration, where trained robot attendants are sufficient.

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NON-DESTRUCTIVE INVESTIGATION OF FLEXURAL PROPERTIES OF CIRCULAR METAL AND PLASTIC HOOPS - - BY MEANS OF DOUBLE FLYWHEELS METHODS

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Keywords: flexural properties, tensile modulus, horizontal and vertical oscillation flywheel sets, thin metal and plastic hoops, non-destructive methods
Abstract: We have suggested a new non-destructive method for measuring of tensile modulus of circular and hoop samples – by means of vertically oriented flywheel set. We had performed a theoretical analysis of its operation and we carried out the testing measurements of simple metal and plastic samples. The results being achieved are compared with the analogous values obtained using the horizontal device.

1 Introduction

The tensile modulus E (also called *elastic modulus* or *Young modulus*) is in here the centre of interest. This quantity belongs to the most important material constants; we can say it is a measure of the stiffness of matter. It determines the relation between stress σ along the axis, and strain ε at axial loading, in the form $\sigma = E.\varepsilon$, which is valid in the range of Hooke's law.

There exist several possibilities how to measure this quantity. The most commonly used way is the static method **-** by stretching /shortening the sample under its force stress. In the case of thin non-linear specimens, such as bent wires, sticks, rods, columns, fibres, and the like (with arc, circular etc. shape) however, its use is problematic; a permanent shape deformation of the material may occur. In such cases, it is advantageous to use some of the dynamic non-destructive methods that are based on the investigation of the intrinsic vibrations of the substances.

One such classical device is a horizontal flywheel set (also known as *Searle's pendulum*). Basically, here are sample oscillations at the three-point bend, which are still damped by flywheels. However, it should be noted that this method is only applicable to partially circular (it means arcuate) samples. For full circular and hoop patterns, the situation is more complicated.

And just creating a device for full circular and hoop samples was the goal of our work. For this purpose, we designed a vertically oriented flywheel assembly.

2 Horizontal coupled flywheel set as an interface to vertical assembly

Since the horizontal device represents a starting step on the path to the vertical set, we will describe it in more details, and the corresponding references and comparison will be related to it, according to scheme

partially circular samples ——→ *fully circular samples*

and

horizontal set ——→ *vertical set.*

Horizontal structure consists of three main parts (Figure 1). There are two horizontal flywheels (mostly cylindrical) 2, fixed to two hinge yarns 1. They are connected by the measured arc-shaped sample 3; this one basically represents the element of "coupling".

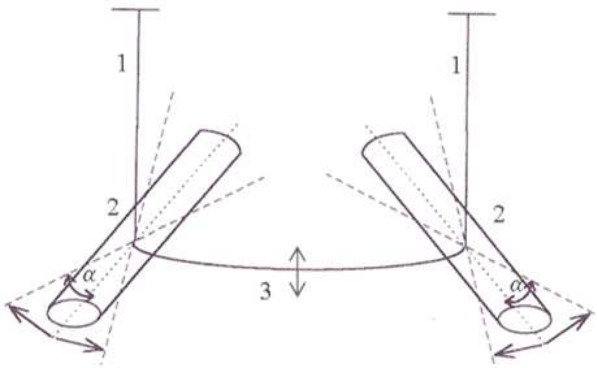

Figure 1 Horizontal flywheel set.
1 – hanging threads, 2 – cylinder flywheels, 3– measured wire (arrows indicate the direction of the oscillations)

Symmetrical deflection of the flywheels in the horizontal direction by the angle α performs the bending oscillating movement of the sample, that is reversely transmitted to the oscillating rotary motion of flywheels - and vice versa. Both parts of a pendulum – i.e. flywheels and sample - oscillate synchronously, with the same frequency and phase. Tensile modulus E can be calculated from a relationship [1], [2] as

$$E = \frac{8\pi l J}{r^4 T^2}, \qquad (1)$$

wherein l is the length of the sample with the radius r. T means the oscillation period of the system, and J is the moment of inertia of the flywheel with respect to the perpendicular axis passing through the centre.
We present a detailed analysis of the measurement procedure using this device - including experimental measurements - in the article [3]. Here (in current paper) we report a comparison of results with vertical set (in Section 4.4 *Results of measurements*).

3 Our work

3.1 Aim of our work

We have suggested new equipment for examination of flexure properties of full circular samples by slowed oscillations – a vertically coupled gravitation set (also known as *coupled reverse pendulums*). Unlike the previous device, the slowing flywheels are located in the vertical direction; the purpose is also to use gravitational forces. A direction the measured sample can be arbitrary – horizontal or vertical; we used a horizontal way. However, the theoretical analysis is more complicated – we need to consider – except for gravity – also the contribution of next factors {see Section 3.3).

3.2 Measuring equipment

A sketch of equipment being used is shown in figure 2. Both reverse pendulums were hung so that they were vibrating in a common vertical plane. When using a classical spring connection for demonstration of composition of parallel oscillations, thus we can determine the spring's stiffness, too.

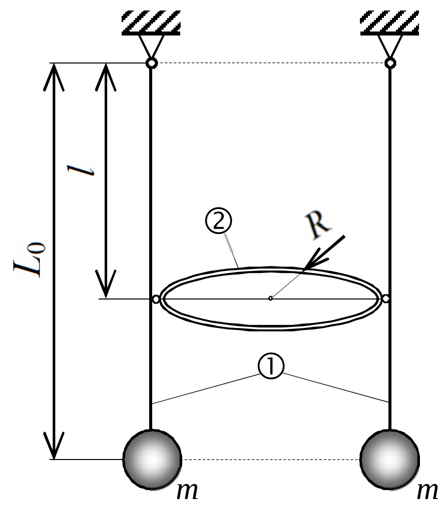

Fig. 2 Measuring equipment scheme.
(1 - pendulums, 2 – circular hoop connecting pendulums)

In our experiment an elastic wire shaped like a horizontal hoop was used as a connection. Deviation of the pendulums in their common plane gave rise to bending vibrations of the wire, while the same phenomenon as in the case of spring connection (i.e. energy transfer from one pendulum to another) could be observed.

Tensile modulus of the wire can be determined similarly as the spring stiffness can be specified. Corresponding basic circular frequencies ω_1 and ω_2 *necessary* for calculation can be determined by experiments from Fig. 3a and 3b examining concordant and/or discordant oscillations of the pendulums.

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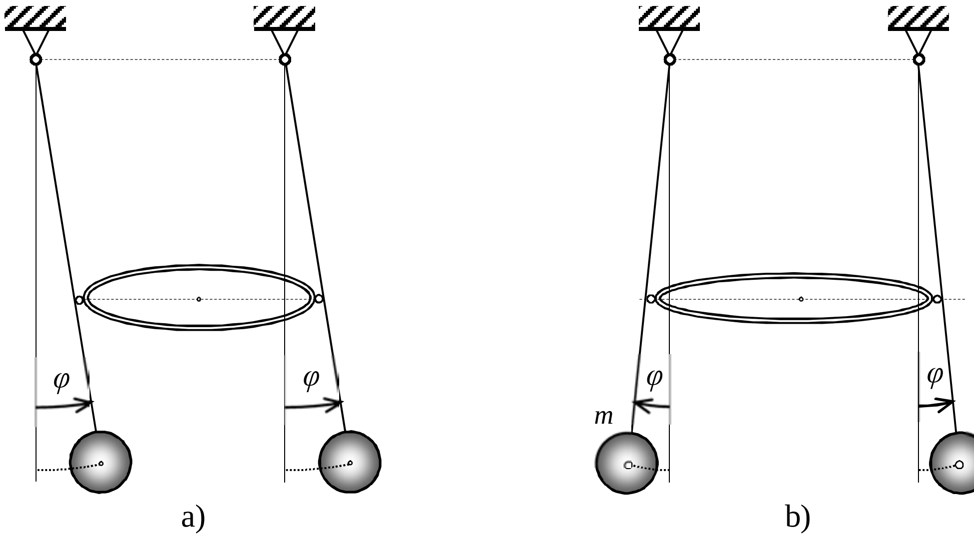

Fig. 3 Vibrational modes of coupled pendulums
a) 1st mode - concordant vibrations, b) 2nd - discordant vibrations

3.3 Dynamic Analysis

In theoretical analysis - compared to a horizontal set - we need to incorporate into our calculations three significant realities:

- the pendulum forces are a mixture of elastic and gravitational activities
- the flywheels do not rotate around their central axes but around the pendulum ones
- the samples are full circular in shape and they are sufficiently thin (for shape deformation)

It is necessary to specify the range of the wire circular deformation caused by the force ***F*** (Figure 4).

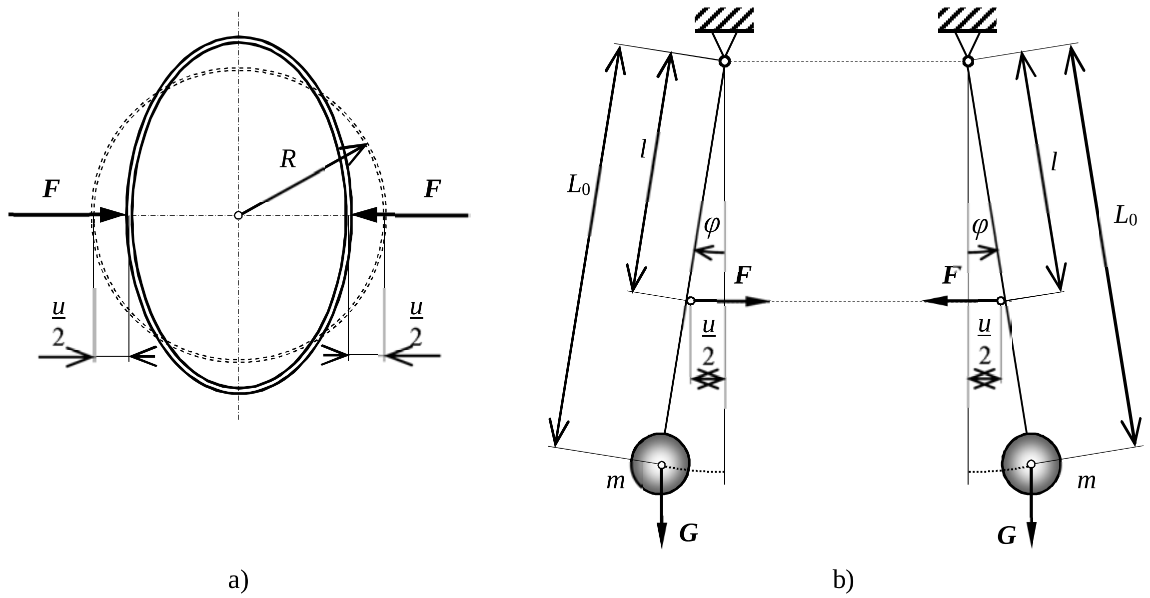

Fig. 4. Deformation diagram at transfer of force F: a) to the circular wire, b) to the pendulum.

(***G*** is weight of pendulum, *u* is a wire deformation; L_0 is distance of the pendulum centre from the rotation axis, *φ* is angle of the pendulum deviation and *l* is distance of the wire connection from the pendulum point).

To do so we used strain energy *A*, the quantity of which is given by bending effects in particular. Regarding perpendicular axes symmetry, the calculation was done only for a quadrant (Figure 5).

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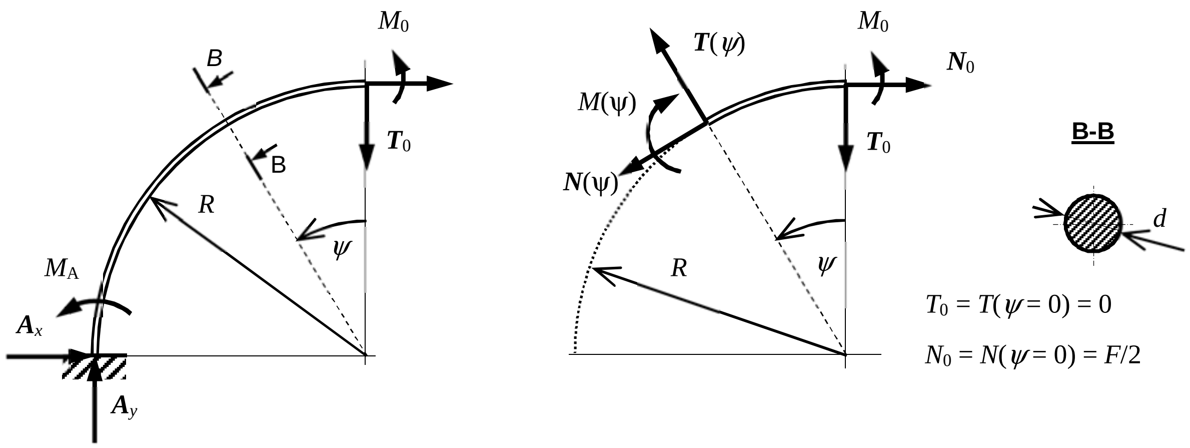

Fig. 5. The analysis of internal forces during deformation of circular wire

Strain energy A of the quadrant is as follows:

$$A = \frac{1}{2EJ_z}\int_0^{\frac{\pi}{2}} M^2(\psi) R \mathrm{d}\psi \tag{2}$$

where

$$M(\psi) = M_0 - \frac{F}{2} R(1-\cos\psi) \tag{3}$$

and E is tensile modulus, J_z is area moment of inertia about wire neutral axis, $M(\psi)$ is bending moment, R is arc radius and ψ represents the angle of turning of the arc. The values of T and N correspond to tangential and normal component of the force F.

Before the calculations it is necessary to determine the value of bending moment M_0, which corresponds to zero rotation at the point $\psi = 0$, i.e.

$$\frac{\partial A}{\partial M_0} = \frac{1}{EJ_z}\int_0^{\frac{\pi}{2}}\left[M_0 - \frac{F}{2}R(1-\cos\psi)\right]R\mathrm{d}\psi = 0 \tag{4}$$

$$M_0 = \frac{F}{2}R\frac{(\pi-2)}{\pi} \tag{5}$$

The value of displacement u_1 at the point $\psi = 0$ can be determined from the following condition:

$$u_1 = \frac{\partial A}{\partial N_0} = \frac{\partial}{\partial N_0}\left[\frac{1}{2EJ_z}\int_0^{\frac{\pi}{2}}(M_0 - N_0 R(1-\cos\psi))^2 R\mathrm{d}\psi\right] \tag{6}$$

Total displacement u is the given by the equation:

$$u = 2u_1 = \frac{FR^3}{4EJ_z}\left(\frac{\pi^2-8}{\pi}\right). \tag{7}$$

Tensile modulus can be determined also from frequencies ω_1 and ω_2 of the connected pendulums. If the interaction between connecting circle element and pendulums is replaced by its force effect, then moment M applied on the pendulum (Figure 3b) can be determined as

$$M = mgL_0 \sin\varphi + Fl\,, \tag{8}$$

where m is pendulum weight and g is gravity acceleration.

Supposing that the pendulums are oscillating in the field of small oscillations ($\varphi < 5°$), $\sin\varphi \cong \varphi$ and $u = 2l\varphi$. Thus, using expressions (7) and (8) we can obtain a new relation:

$$M = mgL_0\varphi + \frac{8\pi l^2 EJ_z}{R^3(\pi^2-8)}\varphi \tag{9}$$

Setting this relation into motion equation of the pendulum we can calculate circular frequency for discordant oscillations of the connected pendulums:

$$\omega_2^2 = \frac{1}{I}\left[mgL_0 + \frac{8\pi l^2 EJ_z}{R^3(\pi^2-8)}\right] \tag{10}$$

where $I = mL_0^2$ is the pendulum inertia moment. A similar relation applies for circular frequency of concordant vibrations of two pendulums:

$$\omega_1^2 = \frac{mgL_0}{I} \tag{11}$$

Having treated the relations (10), (11) and using vibration periods $T_1 = 2\pi/\omega_1$, $T_2 = 2\pi/\omega_2$ and the well-known relation for area moment of inertia (with respect to the axis lying in the bending plane)

$$J_z = \frac{\pi d^4}{64} \tag{12}$$

where d is a wire diameter, we can obtain final relation for calculating tensile modulus of wire in the form of:

$$E = \frac{8(\pi^2-8)mgL_0R^3}{\pi^2 l^2 d^4}\left[\frac{T_1^2}{T_2^2} - 1\right] \tag{13}$$

3.4 Results of measurements

The measurements were carried out by means of connected pendulums as shown in figure 2. We have investigated the elastic properties of several materials – metallic and plastic - all with the same geometric parameters (length l and diameter d). These parameters are summarized in table 1.

Table 1 Geometrical parameters used in our experiments

L_0 [m]	m [kg]	d [mm]	R [m]	l [m]
0.84	0.87	1.5	0.16	0.25

Also the period of concordant vibrations was the same for all materials - $T_1 = 1.040$ s.

So, the only varying parameter had been the period of discordant vibrations T_2. The corresponding results for periods of discordant vibrations are summarized in table 2, together with the relevant values of tensile modules E calculated from the formula (13).

Table 2 Quantities measured for the determination of elastic modulus.

Sample	T_2 [s]	E [GPa]	E_{tab} [GPa]
Steel	0.610	203.3	200 - 210
Aluminium	0.808	69.9	67 - 70
Copper	0.707	124.1	110 -120
Brass	0.759	101.7	90 - 100
Polyamide (nylon)	1.034	1.3	0.9 – 1.4
Polystyrene	1.031	1.8	1.5 - 1.8

As we can see the results being obtained are in good agreement with material-table values (last column); the differences from mean table values represent no more as several per cents.

We also measured - for comparison purposes - the specimens using a classic horizontal assembly. The results obtained were similar to the measurements described, their deviation was a maximum of 10 % compared to the vertical set.

3.5 Statistical evaluation

Another evaluation can be presented in terms of statistical view, based on the accuracy of the single quantities being measured. Therefore, we made a statistical evaluation of the uncertainties, according to the degree of accuracy of the measurements of the individual variables.

It is a rather complicated statistical task. Here we must take into account that the tensile modulus - as can be seen from equation (13) – is a function of four quantities x_i being measured directly, namely $E = f(R,l,T_1,T_2)$; the values of m, L_0 and d were entered directly by the manufacturer and we considered them as constants. In this case – in accordance with theory of measurements - the uncertainty is given by a root, containing partial derivatives with respect to all of the relevant variables and uncertainties of these variables:

$$u_E = \pm\sqrt{\sum_{i=1}^{n}\left(\frac{\partial E}{\partial x_i}u_{x_i}\right)^2} = \pm\sqrt{\left(\frac{\partial E}{\partial R}u_R\right)^2 + \left(\frac{\partial E}{\partial l}u_l\right)^2 + \left(\frac{\partial E}{\partial T_1}u_{T_1}\right)^2 + \left(\frac{\partial E}{\partial T_2}u_{T_2}\right)^2} \quad (14)$$

.

The relevant partial derivatives of (14) are

$$\frac{\partial E}{\partial R} = \frac{24(\pi^2-8)mgL_0R^2}{\pi^2 l^2 d^4}\left[\frac{T_1^2}{T_2^2} - 1\right]$$

$$\frac{\partial E}{\partial l} = \frac{-16(\pi^2-8)mgL_0R^3}{\pi^2 l^3 d^4}\left[\frac{T_1^2}{T_2^2} - 1\right]$$

$$\frac{\partial E}{\partial T_1} = \frac{16(\pi^2-8)mgL_0R^3}{\pi^2 l^2 d^4}\frac{T_1}{T_2^2}$$

$$\frac{\partial E}{\partial T_2} = \frac{-16(\pi^2-8)mgL_0R^3}{\pi^2 l^2 d^4}\frac{T_1^2}{T_2^3}.$$

Here we have set up the precision of measuring instruments for applying the uncertainties of them (e.g. u_R, u_l, u_{T1} and u_{T2}) as the size of the smallest pieces on their scales. So:

$u_R = 1$ mm (ruler)
$u_l = 1$ mm (ruler)
u_{T1} , $u_{T2} = 0{,}01$ s (stopwatch)

After fitting all the variables being relevant we shall get a final value for the resulting uncertainty $U_E \div 8$ %. Thus, the final result can be written – for steel, for example – as

$E = 203.3$ GPa $\pm$ 8 %.

4 Conclusion

The described equipment is simple and illustrative, completing the range of pendulum-based methods for the measurements of elasticity constants. Regarding below 10 % accuracy it ranges to the (relatively) accurate methods. It does non-require intricate measuring equipment and works without destruction, practically. Even extremely thin samples can be measured without a risk of damage or permanent deformation. The activity of pendulums is stable, the system phases do not "tune out" or dump even after several tens or hundreds of oscillations. This method can be successfully used as a demonstration specimen in a university textbook (chapter "Vibrating Movements" or "Solids Physics"), or a task for laboratory exercises.

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