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2) Name of the technical solutions

Program package **JUMPWIND – RSCPR** (rope „**JUMP**y" **WIND**ing (unwinding) process to the complex **RSCPR** system)

3) Key Words

kinematics of jumpy cable winding/unwinding; standard construction of the winch; motion analysis and synthesis.

4) For whom the decision was done (legal entity or industries)

Scientific Research for the purpose of validation of theoretical assumptions.

5) The year when the decision was completed

2016.

6) Year when it began to be implemented and by whom

The program package JUMPWIND – RSCPR implemented in published paper [1], in journal Applied Mathematical Modelling, 2017, appropriate category M21.
We present the confirmation of theoretical contributions in the subtitle **5. The program package JUMPWIND – RSCPR** and in subtitle **6. Testing the defined concept of the dynamics of the rope „jumpy" winding (unwinding) process on the winch during the implementation of the real trajectory of the RSCPR system** using software package JUMPWIND – RSCPR in paper [1]. On this basis the software package JUMPWIND – RSCPR acquires the right to be ranked in the category M81.

7) The area and the scientific field, which the technical solution refers to

Dynamics of the process of the rope winding (unwinding) on the winch belongs to roots of basic research fields: mathematics, geometry with perspective of its kinematic and dynamics models development. Defined result was used as a sub-system of complex RSCPR system in [1]. It means that results from this paper were demonstrated on a complex configuration of a robotic system. However, robotics is not the only scientific area where the results presented in [1] can be used.

8) Problem solved by technical solution

This solution was developed during the implementation of [1]. It does not solve the presented problem but it defines it in detail. The problem defined with program package **JUMPWIND – RSCPR** and with paper [1] was in one part solved with patent in [2] and it will be a topic of research in future publications.

9) State of the problem solution in the world

Problem of the rope „jumpy“ nonlinear in one row radially multilayered winding (unwinding) on the standard shape of winch was not analysed in available world literature. This phenomenon was first analysed in detail in [1] and by program package **JUMPWIND – RSCPR**.

10) Description of the technical solution

This program system **JUMPWIND – RSCPR** was generated in MATLAB. This program package refers to the process of the rope „jumpy“ nonlinear in one row radially multilayered winding (unwinding) on the winch. We deal with the process of the rope „jumpy“ nonlinear in one row radially multilayered winding (unwinding) on the winch through the whole description and because of the easier writing, we will use the shorter term: the rope „jumpy“ winding (unwinding) process.

This analyzes the dynamics of the rope „jumpy“ winding (unwinding) process on the winch. This process is very complicated and its dynamics of the motion affects the motion dynamics of the rest of the mechanism. In this paper, we analyze the dynamics of the rope „jumpy“ winding (unwinding) process on the chosen example of the RSCPR system This phenomenon of the rope „jumpy“ winding (unwinding) process may belong to different classes of mechanisms, not only CPR systems. Therefore, the importance of this research, which deals with the dynamics of the rope „jumpy“ winding (unwinding) process, is much broader because it includes all the classes of mechanisms which are suspended (driven) by ropes.

We develop a kinematic and dynamic model of the rope „jumpy“ winding (unwinding) process. We also analyze the effect of the rope „jumpy“ winding (unwinding) process on the response of the rest of the mechanism. In this paper, we have chosen a particular construction of the system – RSCPR system.

This system is shown in Fig. 1. The RSCPR system consists of three motor – winch subsystems. Each of

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these three subsystems winds (unwinds) its corresponding rope. These three ropes are connected with the camera and they guide it in 3D space. Each motor drives winch that is used for the rope „jumpy“ winding (unwinding) process. Winch is schematically represented in Fig. 2.

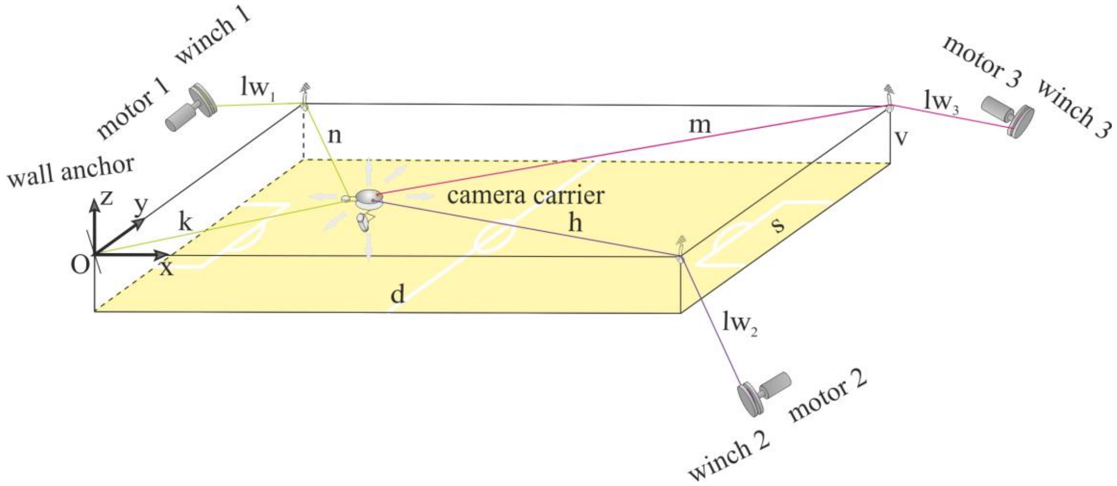

Figure 1 – RSCPR system in 3D space

In the following text we will thoroughly analyse and present the dynamics of the rope „jumpy“ winding (unwinding) process on the winch. The winch has a circular shape of a specified radius. The rope is mounted so that it emerges from this circular surface at a certain place. Fig. 3 shows the starting position of rope „jumpy“ winding (unwinding) process. The starting position was systematically (by calibration) set to be in the direction of the negative part of the x_i axis. Selecting the starting position is very important because it affects the further dynamics of the rope „jumpy“ winding (unwinding) process.

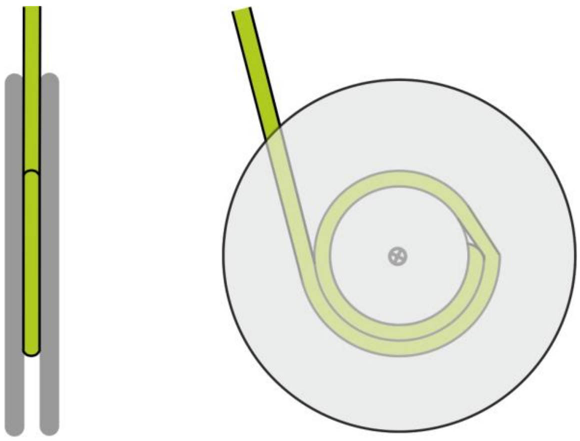

Figure 2 – Winch for single – row radial multilayered rope *un-winding* process

Because of the easier comprehension of dynamics of the rope „jumpy“ winding (unwinding) process, in the following text we will explain the geometry of this process in detail. Correctly generated geometry of the rope „jumpy“ winding (unwinding) process will be of great use for the formation of kinematic model and also the dynamic model of the process.

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Also, because of the easier understanding, we will only explain a rope winding process on the winch in this section and not the unwinding process. Understanding the process of the rope winding on the winch guides the reader to a conclusion that the unwinding process happens with the same phenomena which occur in reverse order.

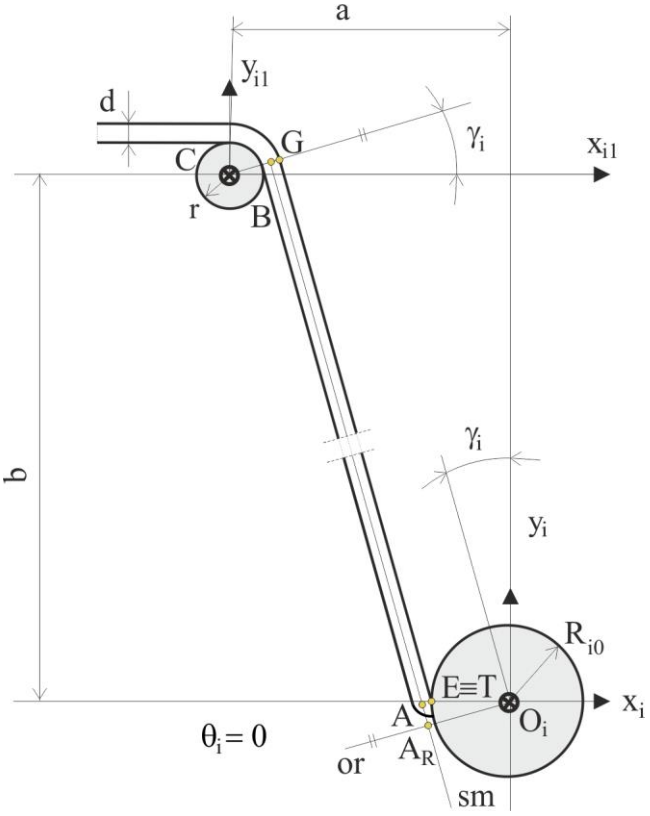

Figure 3 – Starting position of the system

Fig. 3 shows the starting position of the system which consists of the winch radius R_{i0} which is connected with the rope *d* thick. From the other side, the rope goes over the smaller pulley radius *r* and this pulley is stationed at one of the upper corners of the camera's workspace. Behind this pulley, the rope is connected with a camera that continuously acts as a load and tightens the rope. It is important to notice, that the rope is not wound on this pulley, but it is just moves over it. The point *E* represents a place where the rope emerges from the winch. At the starting position of the system for the rope „jumpy" winding (unwinding) process, this point is placed on the negative part of the x_i axis. Point *E* has a fixed position in comparison to the winch, regardless of winches' movement. We presume that the angle θ_i presents the displacement between the line $\overline{O_i E}$ and the negative part of the x_i axis and that angle has the following value at the initial moment $\theta_i = 0^{\circ}$.

Unlike the point *E*, we define the point *T* which constantly changes its position in comparison to the winch. This point presents the position where the rope touches (or at some periods tangents) the winch

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or the rope which was wound until the moment. At the initial moment, points *E* and *T* overlap and that can be seen in Fig. 3. The whole system for the rope „jumpy" winding (unwinding) process on the winch is constructed so that it can be present in a plane like in Fig. 3. Center of the winch is at the point $O_i(x_{iO} = 0, y_{iO} = 0)$, where the $x_i - y_i$ coordinate system is also positioned. The center of the pulley is at the point $C(x_{iC} = -a, y_{iC} = b)$, where the $x_{i1} - y_{i1}$ coordinate system is also positioned. Distance a presents a horizontal distance between the winch's and pulley's axes, while distance b presents vertical distance between these two axes. Winch and pulley are positioned so that $\gamma_i > 0^{\circ}$ for any position of the camera in its workspace. In the initial position of the winding process (see Fig. 3), the angle γ_i has the biggest.

We presume that tension force of the rope always acts through the axis between the winch and pulley – the direction of the line *sm*. At any moment, it is important to determine the radius at which the tension force acts at the winch. In the initial case, the radius represents the distance $\overline{O_\iota A_R}$.

The next position we analyse is shown in Fig. 4 and it is the case when the $\theta_i = \gamma_i$.

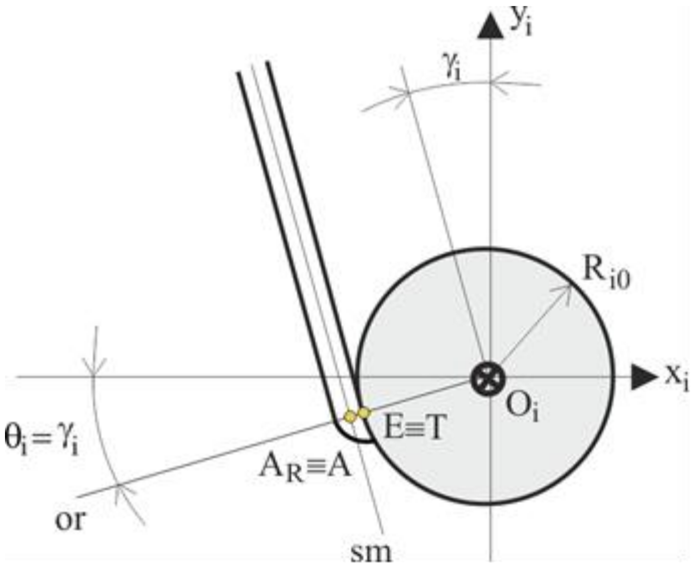

Figure. 4 The position of the system for: $\theta_i = \gamma_i$ – winch zoomed in

Fig. 4 shows the part with the winch. In this specific case, points *A* and A_R overlap and lie on the line $\overline{O_\iota T}$. The rope tangents the winch at the point *T*, at this moment. Also, this is the last moment when points *E* and *T* overlap and from that moment on, the point *E* keeps its fixed position in comparison to winch's motion, while point *T* follows the dynamics of the rope „jumpy" winding (unwinding) process. In this case, the radius has the following value $R_i = \overline{O_\iota A} = \overline{O_\iota A_R} = R_{i0} + d/2$. Also, in this specific case, the distance $lw_i = \overline{AB}$ has the biggest value during the rope „jumpy" winding (unwinding) process.

With the further rope winding, angle θ_i takes the values defined with $\gamma_i < \theta_i < 2\pi + \gamma_i - \alpha_i$.

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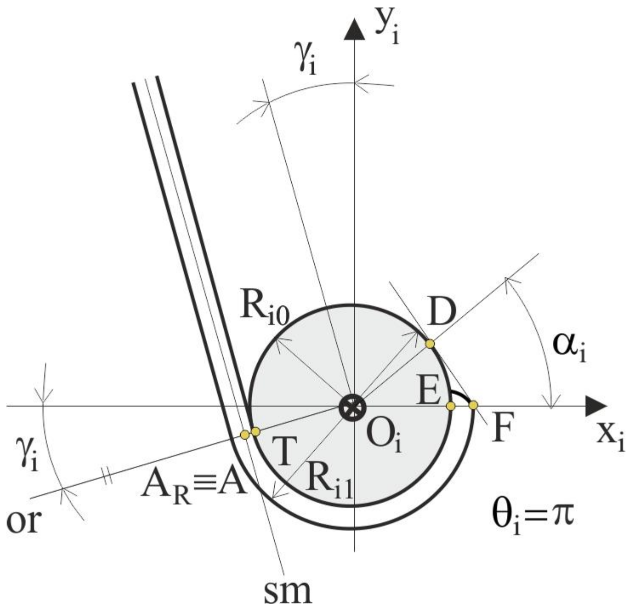

Figure 5 – Determining the angle α_i

This area is named the *con* area (constant). During the *con* area, the winding (unwinding) radius R_i, distance $lw_i = \overline{AB}$ and angle γ_i have constant values and they keep the values achieved when the angle $\gamma_i < \theta_i < 2\pi + \gamma_i - \alpha_i$. In Fig. 5, we can see different positions of points *E* and *T*.

The angle α_i presents one of the constants of the rope „jumpy" winding (unwinding) subsystem and the way in which it is determined is shown in Fig. 5. So, we rotate the winch to the position $\theta_i = \pi$ and then we make a tangent line starting at the point $F(R_{i1}, 0)$, where $\mathrm{R}_{i1} = \mathrm{R}_{i0} + \mathrm{d}$, on the circle with the center at the point O_i and with the radius R_{i0} and in that fashion we determine the point *D*. The angle between the line $\overline{\mathrm{O_i D}}$ and positive part of the x_i axis is angle α_i.

At the moment when $\theta_i = 2\pi + \gamma_i - \alpha_i$, the point *T* touches the rope which connects the winch with the pulley (see Fig. 6). It is an important moment, because from that moment the system exits the *con* area and then we have a new change law of all the important variables: winding (unwinding) radius R_i, distance $lw_i = \overline{AB}$ and angle γ_i. In the next moment, the angle θ_i enters the following area $2\pi + \gamma_i - \alpha_i < \theta_i < 2\pi + \gamma_i$.

We have named this area *jumpvar* area (see Fig. 7). In the *jumpvar* area (variable), radius R_i, distance $lw_i = \overline{AB}$ and angle γ_i are changeable.

The *jumpvar* area is specific for various reasons and because of that, we will particularly analyse this area in detail.

At the first moment of this area, the point *A* suddenly changes its position (compare Figs. 6a) and 6b): in Fig. 6a) point *A* is in the direction of the line *or* at the last moment of the *con* period, while in Fig. 6b) point *A* is in the direction of the line which is parallel with the line *or* but contains the point *T* (line *ta*),

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the first moment of the *jumpvar* period. Because of the current change of the position of the point A, an abrupt change in the value of the distance $lw_i = \overline{AB}$ appears. This causes a significant increase of the first derivative of the variable lw_i at that moment, which reflects negatively on the overall dynamics of the winding (unwinding) subsystem. One example of subsystem's position in the *jumpvar* area is shown in Fig. 7.

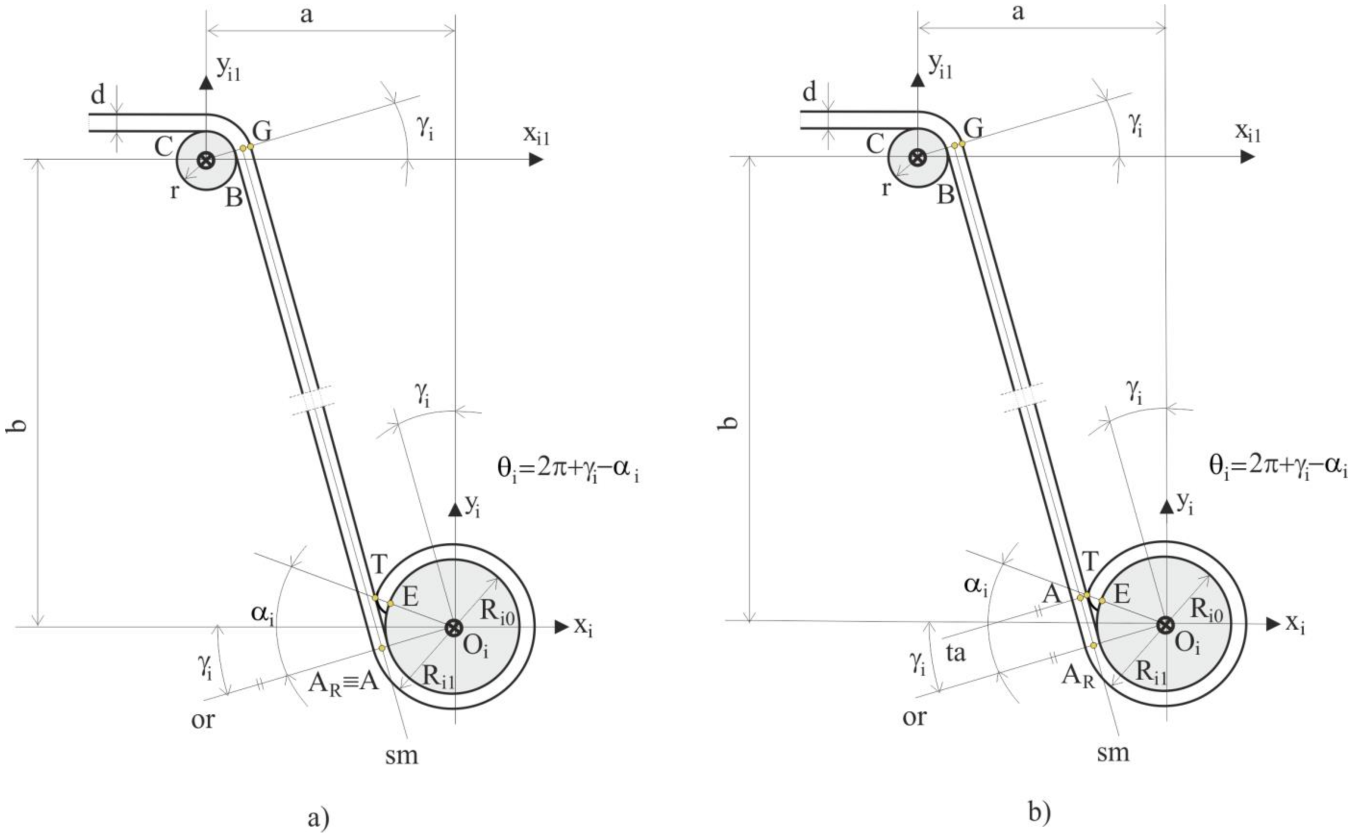

Figure 6 – Position of the system for: $\theta_i = 2\pi + \gamma_i - \alpha_i$, a) the last moment of *con* area, b) the first moment of the *jumpvar* area.

At the first moment of this area, the radius R_i (place where force acts at rope) starts to increase its value. During this period, the radius R_i grows continually from the value $R_i = R_{i0} + d/2$ towards the value $R_i = R_{i0} + 3 \cdot d/2$.

The angle γ_i is determined in the same fashion as in previous moments of the rope „jumpy“ winding (unwinding) process: first we make a tangent line starting at point *T* on the circle which has a center at the point *C* and has a radius of $r + d$. The direction of this line and positive part of y_i axis define the angle γ_i. In *jumpvar* area, angle γ_i decreases constantly.

At the moment when angle β_i achieves the value of the angle α_i, i.e. when the following condition is satisfied $\beta_i = \alpha_i$, the subsystem exits the *jumpvar* area and enters the next *con* area.

At that moment angle θ_i has a value $\theta_i = 2\pi + \gamma_i$. The radius R_i at that moment is $R_i = R_{i0} + 3 \cdot d/2$.

After that moment, the system enters the period when angle θ_i is increasing and has a value $2\pi + \gamma_i < \theta_i < 4\pi + \gamma_i - \alpha_i$.

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Radius R_i, distance $lw_i = \overline{AB}$ and angle γ_i have constant values in *con* area and they keep the values acquired at the moment when angle θ_i reached the value $2\pi + \gamma_i$. In Fig. 8, we show one position of the system in the *con* area defined, i.e. specifically for $\theta_i = 3\pi$. It can be noted that the rope „jumpy“ winding (unwinding) process presents a cyclical alternation of *con* and *jumpvar* phases.

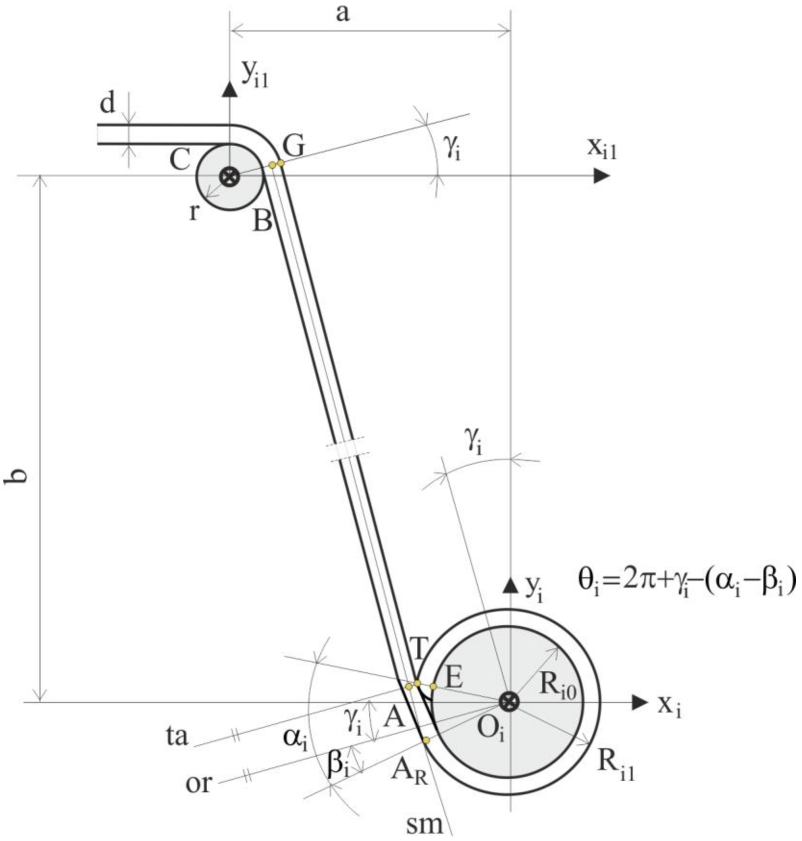

Figure 7 – Position of the system for: $\theta_i = 2\pi + \gamma_i$-($\alpha_i$-$\beta_i$).

Because of the easier understanding of this „jumpy“ concept of the winding (unwinding) process, we have first analysed this concept under idealized circumstances - when the rotational speed of the winch is constant. Firstly, program package JUMPWIND – OW was presented in [1] trough sections 3. Program package JUMPWIND – OW and sections 4. Cyclicality of the rope „jumpy“ winding (unwinding) process on the winch. We use this program package to check and confirm the set of defined mathematical principles. We have defined motion dynamics of only one winch used for the rope „jumpy“ winding (unwinding) process for the trajectory span of: $0 < \theta_i < 17\pi$ [rad]. Defined trajectory is smooth and it is defined with a constant angular speed. This program package was only formed for the winding process of the rope, because it is implied that the rope unwinding is done in the same manner except in the opposite direction. This program package gives the opportunity to user to track the dynamics of change of all the relevant variables: radius R_i, distance $lw_i = \overline{AB}$, angle γ_i and a number of other variables.

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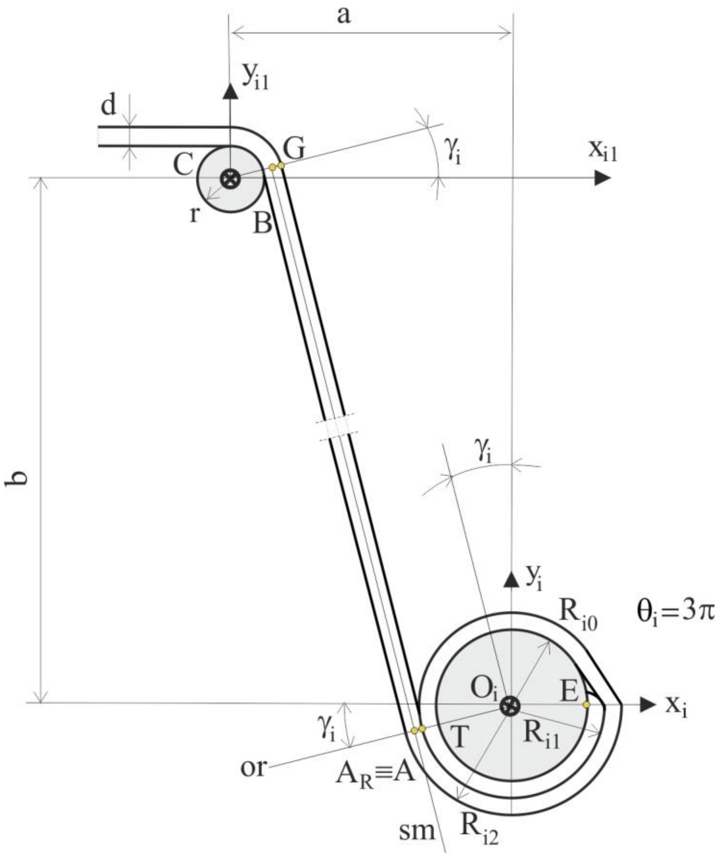

Figure 8 – Position of the system for $\theta_i = 3\pi$.

Dynamics of the rope „jumpy“ winding (unwinding) process is an extremely nonlinear and „jumpy“ process, and it is noticeably reflected on the overall dynamics of the CPR system's response. In order to prove these claims has been synthetized a program package **JUMPWIND – RSCPR**. This program package was developed because we wanted to implement the real feature of the rope „jumpy“ winding (unwinding) process to the complex RSCPR system. The RSCPR system consists of three subsystems for rope winding (unwinding). These subsystems are mutually strongly coupled. Also, these subsystems are coupled with all the other dynamic components of the RSCPR system.

The first research which was based on principles set in program system **JUMPWIND – RSCPR** was published in [1]. The software package **JUMPWIND – RSCPR** is used to verify the validity of the generated mathematical model.

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