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CBRC (Cable-Based Robotic Crane): design and implementation of overhead travelling cranes based on variable radius drums

Lorenzo Scalera, Paolo Gallina, Stefano Seriani and Alessandro Gasparetto

Abstract—In this paper we present a new family of overhead travelling cranes based on variable radius drums, called Cable-Based Robotic Cranes (CBRCs). A Variable Radius Drum (VRD) is characterized by the variation of the spool radius along its profile. This kind of device is used, in this context, for the development of a cable-robot, which can support and move a load through a planar working area with just 2 degrees-of-freedom.

Firstly, we present the kinematic analysis and the synthesis of the geometry of VRD profile. Then, the schema of a bi-dimensional horizontal moving mechanism, based on the VRD theory, and an experimental prototype of a three-dimensional CBRC are presented. The features of this wire-based overhead crane and an analysis of cables tensions are discussed. Finally, the performance of this mechanism is evaluated, demonstrating a deviation between the end-effector and the nominal planar surface of less than 1% throughout the whole working area.

Keywords—cable robot, cable-based robotic crane, overhead travelling crane, variable radius drum, profile synthesis

I. INTRODUCTION

CABLE robots are a special class of manipulators in which flexible cables, rather than rigid links, are used to actuate the end-effector. The main advantages of this class of robot over conventional ones are that cable-based robots can have a larger workspace, they can easily be made to be reconfigurable and modular [1], they are lighter than their rigid-links counterparts, they can be easily transported and their end-effector can achieve high accelerations and velocities. For these reasons, during recent years cable-driven systems have received attention and different kind of cable robots have been investigated. Applications of cable robots span from heavy load and large scale manipulation [2] [3] [4] [5], building tasks [6] [7], to rescue operations [8] and upper limbs rehabilitation [9] [10]. Cables have also been employed in surgical robots to reduce surgeon fatigue and facilitate supervised tele-surgery [11] [12] [13] [14]. Cable-suspended robots are also used to manoeuvre aerial camera systems (sky-cams or spider-cams)

over large areas, such as a stadium [15] [16]. Several cable-suspended parallel robots have been studied and implemented in the recent years. Examples can be found in [17] [18] [19].

Disadvantages of cable-based robotic system include redundancy (as cables can carry load in tension but not in compression) and interference between cables and environment. For these reasons, several researches have been conducted over the years, especially for control purposes [20] [21] [22] [23], dynamic modelling and trajectory tracking [24].

Since cables are used in power transmissions, drive systems and load handling, drums and pulleys have been used in different kind of applications. A drum, or spool, consists of a spindle with flanges, around which a cable is wrapped. The cylindrical surface of an ordinary drum has a constant radius [25]. A typical device, in which an ordinary drum is employed, is a winch [26]. It essentially consists of a movable drum around which a cable is wrapped, so that the rotation of the drum produces a drawing force at the end of the cable. Winches are usually equipped with a ratchet wheel and a pawl to prevent slippage of the load [27].

Examples of research studies in cable-drum systems can be found in [28], where a cable mechanism is used as linear motion sensor, in [29], where a study on the prediction of slip in cable-drum system is proposed, and in [25], where the transmission backlash of a precise cable drive system is analysed and experimentally measured.

While traditionally drums and winches are characterised by a constant radius, in this paper we propose the use of variable radius drum, a mechanical device consisting in a drum with a radius that changes along its profile. As the VRD is rotated by an angle α , a correspondent length of cable is released or wound. This length can be expressed by a non-linear function $g = g(\alpha)$, which depends on the VRD profile and on angular position. With respect to constant radius drums with radius r , where the length of the released cable is given by the linear function $g = \alpha r$, in a VRD it is possible to synthesize a specific profile shape in order to obtain the desired relationship $g = g(\alpha)$. Furthermore, in a VRD a specific profile shape can be defined in order to modify the value of the torque generated by the cable on the VRD itself [30]. The concept of variable radius drum has been introduced in [31].

This paper presents a new family of overhead travelling cranes based on variable radius drums. These cable-driven mechanisms are capable of supporting and moving a load on a planar working area, by using just two degrees-of-freedom.

Section II briefly summarizes related works that can be

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found in literature, Section III gives a general description of a Cable-Based Robotic Crane, Section IV presents the direct kinematic analysis as well as the synthesis of a variable radius drum, whereas in Section V a bi-dimensional horizontal moving mechanism, based on a VRD, is proposed. Section VI reports the inverse kinematic and dynamics of the CBRC, whereas Section VII an analysis of cable tensions. The experimental prototype of the three-dimensional CBRC is presented in Section VIII, whereas in Section IX the experimental results and the performance of this mechanism are presented. Finally, Section X gives the conclusions of this work.

II. RELATED WORKS

Several examples of VRD can be found in literature. Endo et al. proposed a new weight compensation mechanism with a non-circular pulley and a spring [32]. Kilic et al. used a wrapping cams mechanism in the synthesis of non-linear torsional spring [33], whereas a similar methodology has been used by Schmit and Okada to develop a non-linear rotational spring [34]. Furthermore, a non-constant radius pulley for antagonistic springs was proposed by Kim and Deshpande [35]. Shin et al. developed a methodology to synthesize variable radius pulleys to improve joint torque capacity in pneumatic artificial muscles, used as actuators for Stanford Human-Friendly Robot [36]. An application of VRD in locomotion is given by Kljuno et al., who developed RoboCat, a quadruped cable-driven robot [37]. From a kinematic point of view, the synthesis of a variable radius drum was approached by Gallina on a particular case of rocker-belt mechanism [38].

Concerning traditionally overhead cranes, the main research area is, nowadays, the dynamical modelling and control, in order to eliminate swing effects and ensure system stability. Examples can be found in [4] [39] [40] [41] [42].

With respect to traditionally overhead cranes, Cable-Based Robotic Cranes do not require rails or linear guides along the whole span of the system since they are essentially composed of a series of pulleys, drums and cables. For this reason, their frame is lighter and can be easily disassembled. Furthermore, they are modular and their accuracy only depends on the positioning of the pulleys supports in the set-up phase. Cartesian robots are characterized by a high stiffness and are employed in the handling of small workspaces, where they are extremely accurate for high precision pick-and-place tasks. On the contrary, our device is meant for the handling of large amount of materials in very large workspaces, where the weight of the structure can be a problem. One possible application could be the loading and unloading of materials and supplies for general naval applications, where the workspace is large, the infrastructures have to be light and accuracy is much less demanding. Furthermore, the proposed mechanism could also be deployed as a 2D aerial overhead conveyor for industrial or even mining application, where vertical motion is not required. On the other hand, it has to be noticed that, in the cases in which a movement of the load in the vertical direction is needed (such as for pick-and-place tasks), a winch could be mounted on the end-effector of the robotic crane.

To the best of the Authors' knowledge, no examples of overhead travelling cranes based on cables and variable radius drums can be found in the previous literature.

III. CBRC DESCRIPTION

In this section the description of a Cable-Based Robotic Crane is presented. A graphic representation of this three-dimensional overhead travelling crane based on variable radius drums can be seen in Fig.1.

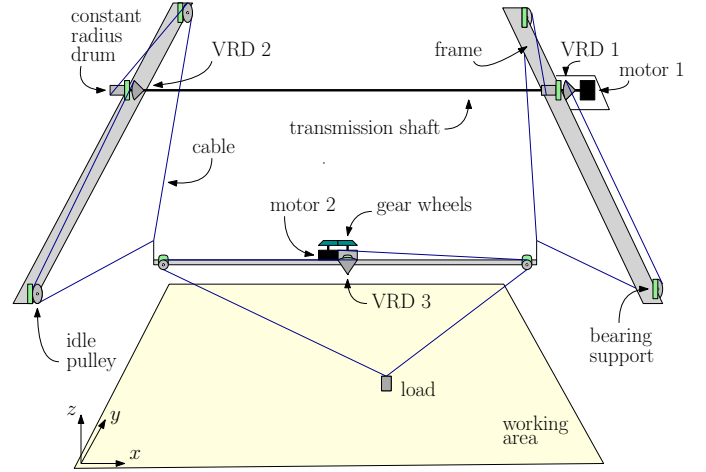


Fig. 1: Graphic representation of a Cable-Based Robotic Crane.

The experimental prototype is composed of three Horizontal Moving Cable-Mechanisms (HMCs) identical in size that allow the motion of a load within a planar working area. The two upper mechanisms, identified by VRD 1 and 2, are positioned at the same vertical height in a parallel position. The end-effector of each of this two upper systems is then connected to one edge of the frame of the third mechanism. Thereby, the lower frame, identified by VRD 3, can be moved horizontally through y axis. HMCs 1 and 2 are connected by means of a transmission shaft, which ensures that they have the same angular position α . The third HMC is located on the lower frame and enables the motion of the load through x axis. In this way, the 2 DOFs CBRC allows the motion of a load through a rectangular working area.

The CBRC prototype is actuated by two motors: the first is directly connected to the upper transmission shaft and ensures the motion through y axis, whereas the second, which ensures the actuation along x axis, is located on the shifting frame and transmits the motion to VRD 3 by means of two gear wheels.

IV. KINEMATIC ANALYSIS AND SYNTHESIS

In this section the kinematic analysis of a variable radius drum for each HMC is briefly summarize. In Fig.2 a graphical representation of the VRD is reported. On the left, the VRD is constrained in point O by means of a revolute joint, whereas, on the right, an idle pulley is fixed in point P_b with another joint of the same type. The cable is fixed at one end of the VRD in point F , it is wound around the

drum profile and, initially, it is separated from the VRD in the tangent point P_t . We define A this tangent point fixed at the VRD, at initial conditions, as shown in Fig.2(a). The cable is then wrapped around the idle pulley and it is tangent to its surface in points E and C_0 . On the VRD a marker has been placed in order to easily identify the rotation of the drum with respect to the reference frame, given by angle α . We assume α positive in clockwise direction. In order to introduce the parameters that characterize the kinematic analysis of the VRD, we consider two different configurations of the drum: the case with $\alpha = 0$ and the one with $\alpha > 0$, reported respectively in Fig.2(a) and 2(b).

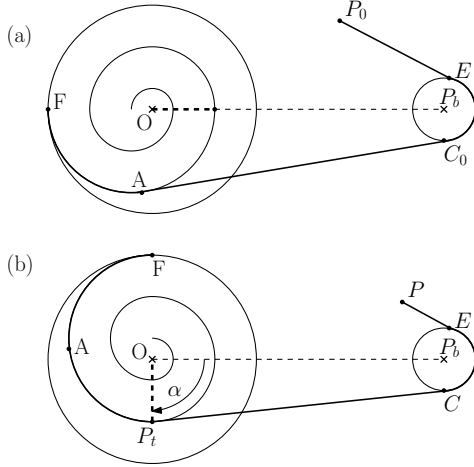


Fig. 2: Kinematic Analysis of a Variable Radius Drum.

1) *Case $\alpha = 0$:* In this configuration we assume that the system is in equilibrium. A proper torque acting on the VRD along the counter-clockwise direction is present as well as a force which pulls the cable and balance the torque action. When $\alpha = 0$, we define l_0 the total length of free cable, not wound around the drum, from point P_0 to the tangent point A . The length of l_0 is given by:

$$l_0 = \|\mathbf{AC}_0\| + \widehat{C_0E} + \|\mathbf{EP}_0\| \quad (1)$$

With the symbol $\widehat{}$ we indicate arcs as well as curved segments on the VRD.

2) *Case $\alpha > 0$:* In this configuration the drum has rotated in clockwise direction of an angle $\alpha > 0$. A segment of cable length $\widehat{AP_t}$ is wound around the variable radius drum. The length of the segment PE has now changed with respect to the previous configuration: in particular, the length of PE is a function of α and of the shape of the VRD. We obtain:

$$\|\mathbf{P_tC}\| + \widehat{CE} + \|\mathbf{EP}\| = l_0 - \widehat{AP_t} \quad (2)$$

The length of cable wound by the VRD during its rotation is a function of angular position. We define this function $g(\alpha)$:

$$g(\alpha) := \|\mathbf{EP}_0\| - \|\mathbf{EP}\| \quad (3)$$

By replacing Eq.(1) and (2) into Eq.(3), we obtain:

$$g(\alpha) = (\|\mathbf{P_tC}\| - \|\mathbf{AC}_0\|) + (\widehat{CE} - \widehat{C_0E}) + \widehat{AP_t} \quad (4)$$

Three addends contribute in Eq.(4): the first is the difference between the length of the cable tangent to the variable radius drum and the idle pulley in case $\alpha = 0$ and $\alpha > 0$, the second is the difference between arcs on the idle pulley when $\alpha = 0$ and $\alpha > 0$, the third is the curved profile of the VRD on which the cable is wound.

A. Direct Kinematic Analysis

The Direct Kinematic Analysis aims to calculate the relationship between the function of wound cable $g(\alpha)$ and the angular position of the variable radius drum α , by knowing the geometry of the VRD profile. In order to do so, we define $\phi = \phi(\alpha)$ as the angle of the tangent point P_t with respect to horizontal line and considered positive in clockwise direction (see Fig.3). We express the profile of the VRD geometry in polar coordinates, as $\rho = \rho(\beta_r)$. We assume the angle β_r positive in the counter-clockwise direction with respect to the frame fixed to the VRD (relative reference frame). Then, the direct kinematic analysis can be developed by solving the integral of the VRD curve:

$$g(\alpha) = (\|\mathbf{P_tC}\| - \|\mathbf{AC}_0\|) + (\widehat{CE} - \widehat{C_0E}) + \int_{-\phi(0)}^{\alpha - \phi(\alpha)} \sqrt{\rho^2 + (d\rho/d\beta_r)^2} d\beta_r \quad (5)$$

In Eq.(5), both the addends $(\|\mathbf{P_tC}\| - \|\mathbf{AC}_0\|)$ and $(\widehat{CE} - \widehat{C_0E})$ are non-linear functions of the angular position α . Their calculation depends on the function $\rho(\beta_r)$ and it has to be analysed case by case.

B. Variable Radius Drum Synthesis

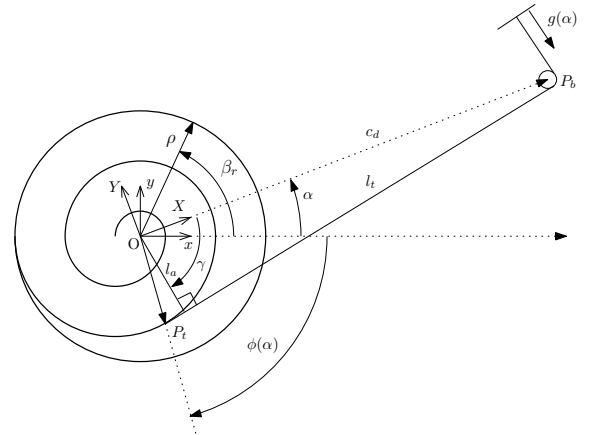


Fig. 3: Variable radius drum parameters in case of point-like idle pulley and neglected cable thickness.

In Fig.3 it can be seen that, as the VDR rotates in clockwise direction, the idle pulley is seen, by an observer on the drum,

rotating in the counter-clockwise direction of the same angle. The unit vectors \mathbf{x} and \mathbf{y} define the reference frame of the VRD, whereas the unit vectors \mathbf{X} and \mathbf{Y} define the inertial reference frame, with respect to the VRD, fixed to the idle pulley centre P_b . In this initial approach to the problem, the idle pulley is assumed to be point-like, with a radius equal to zero. In this configuration, we define c_d the distance between the idle pulley and the centre of the VRD, l_t the distance between tangent point P_t and the idle pulley centre, γ the angle between the segment OP_b and the minimum distance between the cable and the centre O of the VRD. The aim of the synthesis is to calculate the profile of the VRD by knowing the wound cable length function $g(\alpha)$.

In local coordinates, the tangent point P_t can be written as a sum of two vectors: the first from O and P_b , $\{c_d \ 0\}^T$, the second from P_b and P_t , $\{l_t \ 0\}^T$:

$$P_t = T(\alpha) \begin{Bmatrix} c_d \\ 0 \end{Bmatrix} + T(\alpha)T(-\gamma)T\left(-\frac{\pi}{2}\right) \begin{Bmatrix} l_t \\ 0 \end{Bmatrix} \quad (6)$$

where the operator $T(x)$ is the rotation matrix between two reference frames rotated by an angle x .

The whole mathematical derivations to obtain the VRD profile synthesis are reported in Appendix A. Finally, the geometry of VRD profile, in Cartesian coordinates, is given by the following equation (Eq.(31) in the appendix):

$$c_d \sin(-\gamma) + \left(1 - \frac{d\gamma}{d\alpha}\right) l_t = 0 \quad (7)$$

where l_t is equal to:

$$l_t = \frac{c_d \sin \gamma}{1 + \frac{\frac{d^2 g}{d\alpha^2}}{\sqrt{c_d^2 - \left(\frac{dg}{d\alpha}\right)^2}}} \quad (8)$$

and γ can be written as:

$$\gamma = \cos^{-1} \left(\frac{1}{c_d} \frac{dg}{d\alpha} \right) \quad (9)$$

The necessary conditions for the existence of a solution for the VRD synthesis problem is the continuity of $g(\alpha)$ and its derivative. Furthermore, from Eq.(8) it has to be noticed that it is necessary that $dg/d\alpha < c_d$. This fact suggests that the idle pulley has to be located at a proper distance from the variable radius drum.

In Appendix B, the VRD synthesis is reported by considering the radius of the idle pulley and the cable thickness.

V. HORIZONTAL MOVING CABLE-MECHANISM

Before presenting the prototype of a Cable-Based Robotic Crane, which will be illustrated in Section IV, we propose the schema of a bi-dimensional HMCM based on a variable radius drum, by applying the theory developed in Section II.

A horizontal moving cable-mechanism (Fig.4), which is a module of the crane, is capable of moving a load along a linear path, parallel to the x axis. This cable-based device can be developed by having recourse just to pulling cables, revolute

joints, a regular drum and a variable radius drum. It has to be noted that no prismatic joints are required.

Conventional planar cable-based robots or mechanisms, which act in vertical plane and are subjected to gravity force, are, in general, two degrees-of-freedom (DOFs) systems. The most common configuration of this kind of mechanisms is in the form of a triangle and a load is suspended through two cables between the related motor-drums. The two actuators need to be correctly controlled, if, for example, the load has to be carried through a linear path and a trajectory parallel to the ground has to be followed. Hence, the path planning of such systems acts on a 2 DOFs system. Here, on the contrary, we present a mechanism able to reach the same target using just 1 degree-of-freedom.

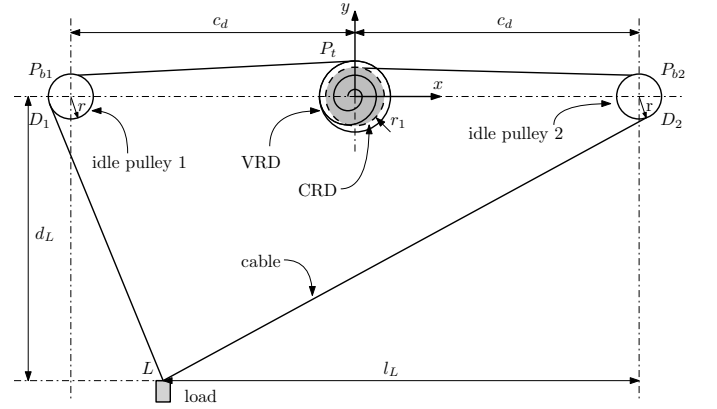


Fig. 4: Graphical representation of a horizontal moving cable-mechanism based on a variable radius pulley.

The HMCM, proposed in Fig.4, is composed of a VRD, a constant radius pulley (which radius is r_1 and it is represented in grey), two idle pulleys (that revolute around points P_{b1} and P_{b2} and have each one radius equal to r), and the load. The latter, represented by a little grey rectangle, is assumed to have mass m at point L , where m is the third HMCM load for the first two modules whereas the load of the end-effector for the third HMCM. The mechanism is located in the vertical plane and, therefore, gravity force is acting on the mass, which is connected by two cables at point L . In this context, we assume cable thickness to be null. The left cable goes around the idle pulley, constrained in P_{b1} , and it is then wound around the variable radius pulley. On the contrary, the right cable goes around the idle pulley, fixed in P_{b2} , and then it is wound around the constant radius pulley. It has to be noticed that the VRD and the CRD are connected to the same shaft and, therefore, they have the same angular position α . In Fig.4, c_d indicates the distance between the centres of the lateral pulleys and the centre of the variable and constant radius drums, whereas d_L is the distance between the horizontal linear path of the load and the x axis. Finally, l_L indicates the horizontal distance between point L of the load and the vertical segment intersecting the centre of the right idle pulley P_{b2} . The angular position α of the VRD is considered positive in the clockwise

By considering that:

$$\theta_2 = \frac{r_1}{r} \alpha = \frac{r_1}{r} \tilde{f}(x) \quad (20)$$

for symmetry we can easily obtain the expression of θ_1 in function of angle α :

$$\theta_1 = -\frac{r_1}{r} \tilde{f}(-x) = -\frac{r_1}{r} \tilde{f}(-\tilde{f}^{-1}(\alpha)) \quad (21)$$

where the direct kinematic equation $x = \tilde{f}^{-1}(\alpha)$ has been taken into account.

Finally, by calculating the derivative function with respect to α , the expression of the transmission ratio between the VRD and the idle pulley 1 is obtained:

$$\tau_{\alpha, \theta_1} = \frac{\dot{\theta}_1}{\dot{\alpha}} = \frac{r_1}{r} \frac{\tilde{f}'(-x)}{\tilde{f}'(x)} = \frac{r_1}{r} \frac{\tilde{f}'(-\tilde{f}^{-1}(\alpha))}{\tilde{f}'(\tilde{f}^{-1}(\alpha))} \quad (22)$$

VII. CABLE TENSION ANALYSIS

In this Section we present an analysis of tensions in the cables of the CBRC. For the sake of simplicity, we consider the bi-dimensional horizontal moving mechanism presented in Section III. In Fig.6, a graphical representation of cable tensions T_1 and T_2 in the robotic crane is shown. L is the weight force, whereas θ_1 and θ_2 are the angles between the cables and the vertical plane. It has to be noticed that, in this analysis, the idle pulleys as well as the VRD and the CRD are considered to be point-like.

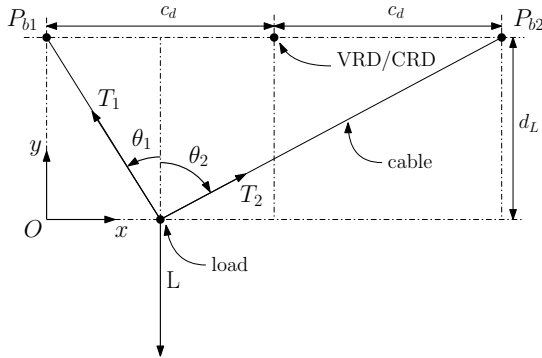


Fig. 6: Graphical representation of cable tensions in the HMCM.

By solving the horizontal and vertical equilibrium equations system, the two tensions can be easily obtained:

$$\begin{aligned} T_2 &= \frac{L}{\sin(\theta_2) \frac{\cos(\theta_1)}{\sin(\theta_1)} + \cos(\theta_2)} \\ T_1 &= T_2 \frac{\sin(\theta_2)}{\sin(\theta_1)} \end{aligned} \quad (23)$$

In order to make the examination non-dependent from distance d_L and from inter-axle spacing c_d , we introduce the parameter d , defined as $d := d_L/2c_d$. Furthermore, the tensions T_1 and T_2 are divided by the weight force mg , whereas the x coordinate by the distance $2c_d$.

In Fig.7 the trend of tension T_1 over the x axis, for different values of the parameter d , is reported. It has to be noticed that only tension T_1 has been reported, since the two tensions are symmetric with respect to the central vertical axis of the mechanism, corresponding to a value of $x = 0.5$.

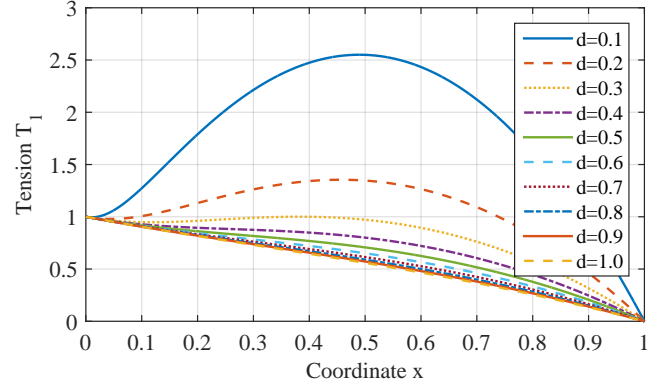


Fig. 7: Tension T_1 over the x axis, for different values of parameter d .

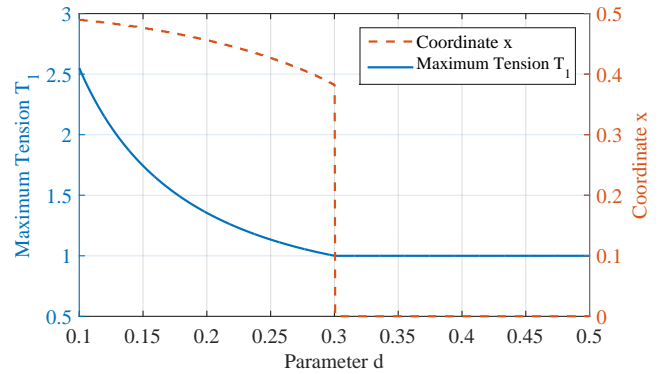


Fig. 8: Maximum tension T_1 and its position on x axis with respect to d .

In Fig.8 the maximum tension T_1 and its position on the x axis with respect to parameter d are reported. As it can be seen, for $d = 0.3$ a discontinuity point in the position of the x coordinate is present and, for values of d greater than this value, the maximum tension in the cable is equal to the weight force. This examination can be useful in the first stage of the design of a CBRC, when the vertical distance of the end-effector with respect to the pulleys horizontal height has to be chosen. Additionally, it has to be noticed that the torque required to maintain the load in a equilibrium point is null. This is because the potential energy is constant since the load moves along a horizontal path.

VIII. PROTOTYPE OF THE CABLE-BASED ROBOTIC CRANE

A general overview of the experimental prototype is reported in Fig.9. Before describing the features of the experimental

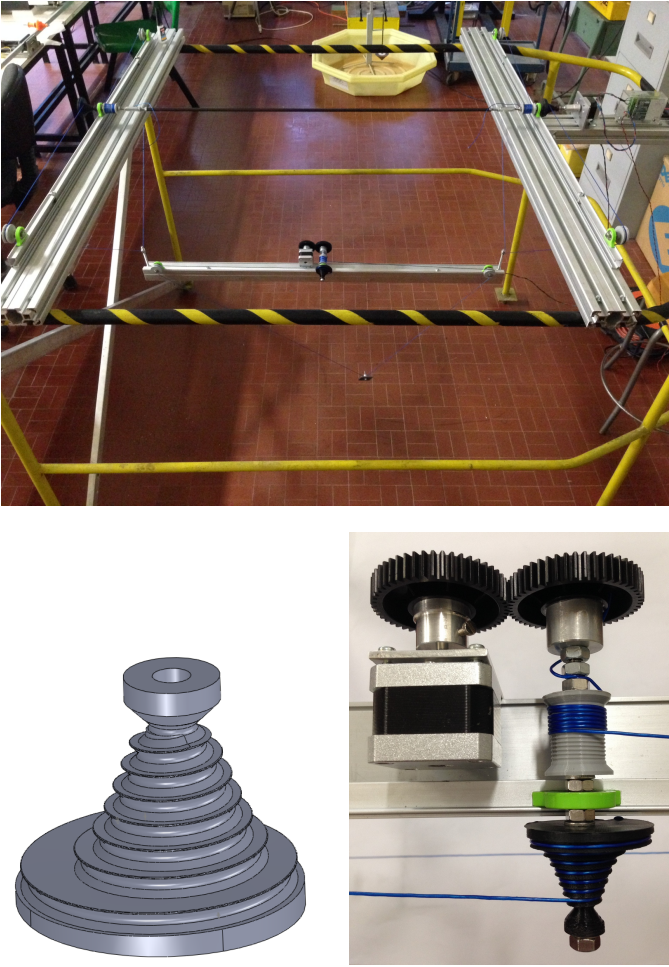


Fig. 9: Experimental prototype of the Cable-Based Robotic Crane. On the top a general overview of the experimental set-up can be seen. On the bottom-right corner the actuator system, the gear wheels and the VRD 3 are shown, whereas on the bottom-left corner the 3D model of the VRD is reported.

prototype, it is necessary to underline that the fabrication of a variable radius drum is a critical aspect, since its shape can not be easily obtained by means of traditional manufacturing processes. In order to obtain a working prototype, we have used 3D printing fused deposition modelling (FDM) technology, which allows the creation of free-form shapes by means of a 3D modelling software. Not only the VRDs, but also the CRDs, the idle pulleys and the bearing supports have been produced with 3D printing technology in PLA plastic. The upper and lower frames of the CBRC have been realized with aluminium profile shapes, whereas the transmission shaft has been built in carbon. With reference to Fig.4, the geometrical parameters for each of the three single HMCM that composes the experimental CBRC are: $c_d = 500 \text{ mm}$, $d_L = 500 \text{ mm}$, $r = 15 \text{ mm}$ and $r_1 = 10 \text{ mm}$. In this prototype, a load with a mass equal to $m = 0.550 \text{ Kg}$ has been chosen. As actuators,

we used two 12 V powered NEMA 17 stepper motors, which have been chosen for the compact shape, lightweight and output torque properties. The motors are driven by two L293D drivers directly controlled by an Arduino® UNO rev.3 micro-controller board, based on the ATmega 328P.

In order to measure the cable tensions, we developed a proper measurement system, reported in Figure 11. It consists in three 3D printed idle pulleys and a Phidgets micro load cell that allow to measure the cable tension in the vertical direction. The load cell has been calibrated and the data acquired by means of a SparkFun OpenScale board.

As it can be noticed from the figures and the graphic representations, the variable radius drums and the constant radius drums are not planar, but they are in the form of a helical cone and a cylinder respectively. Except when the spiral angle is less than 360 degrees, purely planar VRDs and CRDs are impossible to build. This fact introduces an error with respect to the mathematical theory developed in Section III and IV, which is inherent to purely planar mechanisms. As it can be seen in Fig.9, the idle pulleys and the drums are not coplanar. In fact, as the bearings supports (printed in green plastic) for both idle pulleys and drums shafts are mounted on the same plane, a small offset between the tangent point of the cable on the drums and the tangent point of the cable on the pulleys is present. This deviation produces an error source with respect to the nominal behaviour of the mechanism but, for the sake of simplicity, it has been neglected in this context.

Finally, the most important error sources that affect the CBRC can be summarized in the following list:

- manufacturing errors;
 - mathematical approximation in the VRD synthesis (see Eq.(14), namely $D_1(0)\widehat{D}_1(\alpha) \simeq 0$ as well as $D_2(0)\widehat{D}_2(\alpha) \simeq 0$);
 - non-planarity of the idle pulleys and drums;
 - geometrical errors;
 - misalignment of the pulleys and drums axis;
 - cables elongation and elasticity [4] [12] [43];
- Cables elongation Δx with respect to the nominal length x_0 can be calculated with the following equation:

$$\Delta x = \frac{T(x)}{AE} x_0 \quad (24)$$

where $T(x)$ is the cable tension, A is the cross-sectional area of the cable, whereas E the Young's modulus. In the plastic cable employed in our prototype $EA \simeq 13 \text{ kN}$. In particular, with respect to Fig.6, the accuracy errors Λ_x and Λ_y in x and y directions, due the cable elasticity and relative to the payload, can be evaluated as follows:

$$\Lambda_x = \frac{|x_E - x_L|}{mg} \quad \Lambda_y = \frac{|y_E - y_L|}{mg} \quad (25)$$

where (x_L, y_L) and (x_E, y_E) are the end-effector coordinates in nominal position and the ones affected by cable elongations, calculated with Eq.s (23) and (24). Fig.10 reports the trend of these errors along the x axis.

- scale errors;

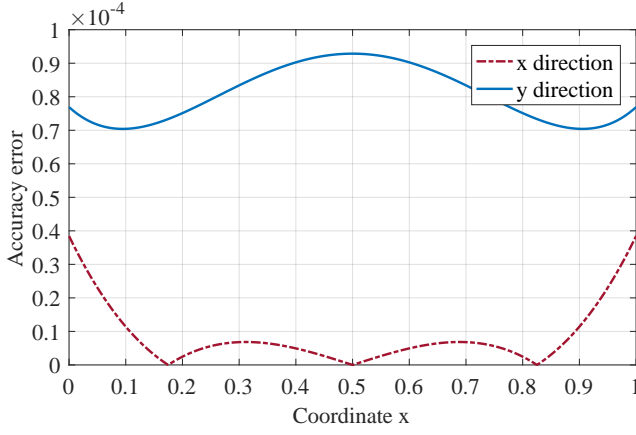


Fig. 10: Accuracy errors Λ_x and Λ_y , relative to the payload, over the x axis (a value of $d = 0.5$ has been chosen).

The scale error e_x for a single HMC (Fig.6) affects the measure on the end-effector position along the x axis, resulting in the following error:

$$e_x = \frac{(K_1^2 - 1)l_1^2(\alpha) - (K_2^2 - 1)l_2^2(\alpha)}{2L^2} \quad (26)$$

where K_1 and K_2 are the scale factors on idle pulleys 1 and 2 respectively, $l_1(\alpha)$ and $l_2(\alpha)$ are the length of the free-cables 1 and 2 in function of the free-coordinate α and $L = 2c_d$.

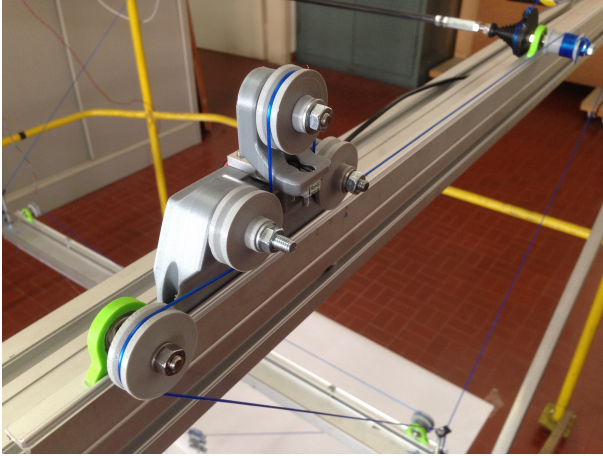


Fig. 11: Cable tension measurement system.

IX. EXPERIMENTAL RESULTS

The performance of the Cable-Based Robotic Crane here presented can be evaluated by measuring the deviation of the end-effector from a nominal planar surface. In order to do so, a grid has been marked out on the working area of the overhead travelling crane and the height of the load has been measured, in static conditions, by means of a vertical calliper through

the surface in both x and y directions. On the working area a sampling interval has been chosen of $\Delta x = 50 \text{ mm}$ and $\Delta y = 50 \text{ mm}$ starting from $(x = 0, y = 0)$ till $(x = 700 \text{ mm}, y = 700 \text{ mm})$.

In Fig.12 the experimental results are shown. The red dots indicate the measure points, whereas the blue planar surface is the nominal plane. As it can be seen, the maximum deviation from the theoretic path is actually really small and equal to 5.8 mm . At this value it corresponds a maximum relative error of 0.83% to the total length of the path in one direction (700 mm). It can be appreciable how the relative error is very small and lower than 1% throughout the whole working area.

Furthermore, the errors along x and y axis have been evaluated in order to provide the positional accuracy of the upper and lower HMCs separately. In particular, errors in the x direction have been evaluated by fixing the upper HMCs and moving only the lower HMC. In the same manner, y errors refer to the centre of the frame of the lower HMC, when only the two upper mechanisms are activated. As we have done for the evaluation of vertical accuracy, measures in x and y directions have been acquired in static conditions. In fact, measurements have been taken after the dynamic oscillations became negligible. In Figs. 13 and 14 the absolute experimental errors in x and y directions respectively are reported. Table I summarizes the statistical analysis of the absolute errors in the three directions. As it can be seen, a Kolmogorov-Smirnov test has been applied to the errors in order to verify the normal distribution of data. These results

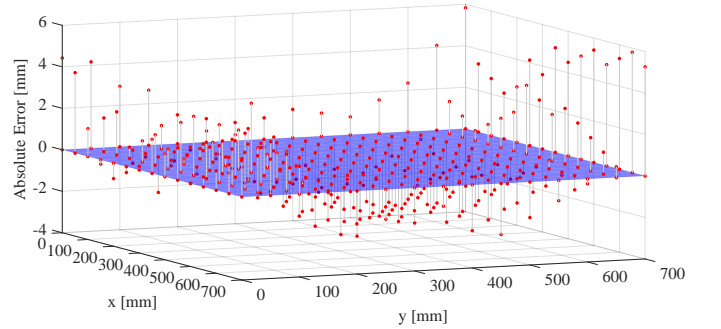


Fig. 12: Absolute experimental error with reference to nominal planar surface.

show that the experimental prototype, even in this early stages of development, can achieve its task with acceptable accuracy and precision. Moreover, the offset of the drums does not produce a worrying effect on the performance of the global mechanism. The deviation error could be further reduced by using more accurate manufacturing technologies for the VRD and the pulleys, with respect to 3D printing technique, e.g. milling machine manufacturing.

Finally, the cable tensions of the presented prototype have been measured in order to compare them with those previously computed in Section VII (case $d = 0.5$ in Figure 7). The results are reported in Figure 15. For each point 6 different measures have been acquired and the statistical analysis of the data is reported in Table II. In particular, the results have been divided

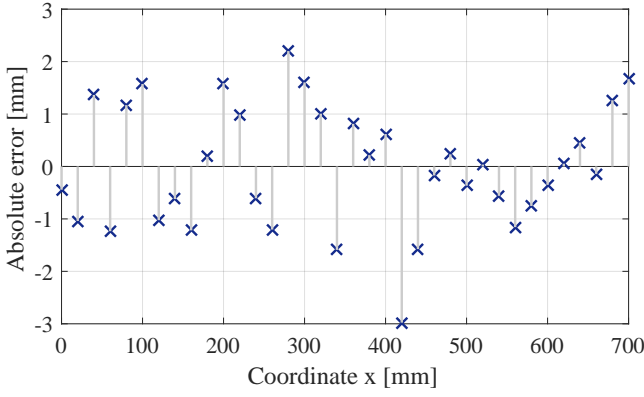


Fig. 13: Absolute experimental error in x axis.

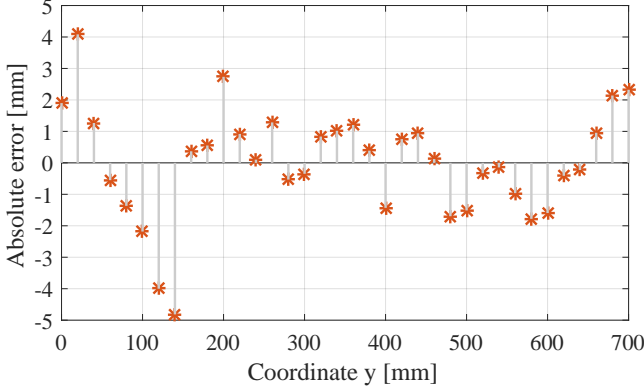


Fig. 14: Absolute experimental error in y axis.

TABLE I: Statistical analysis of absolute errors [%].

Axis	Max	Mean	St. Dev.	p -value (K.-S. test)
x	0.4254	0.1352	0.0938	< 0.05
y	0.6880	0.1895	0.1626	< 0.05
z	0.8326	1.6858	1.1992	< 0.05

by mg , where m is the mass of the load used in the measures, in order to compare them with the theoretical data. As it can be seen from Figure 15, a good agreement between the theoretical curve and the experimental results can be appreciated.

TABLE II: Experimental cable tension errors in function of x position with respect to theoretical data ($d = 0.5$).

x -coord. [mm]	Max	Mean	St. Dev.
150	0.0556	0.0336	0.0181
250	0.0427	0.0237	0.0173
350	0.0402	0.0237	0.0172
450	0.0421	0.0231	0.0183
550	0.0415	0.0189	0.0191
650	0.0334	0.0159	0.0131
750	0.0224	0.0130	0.0058
850	0.0268	0.0130	0.0095

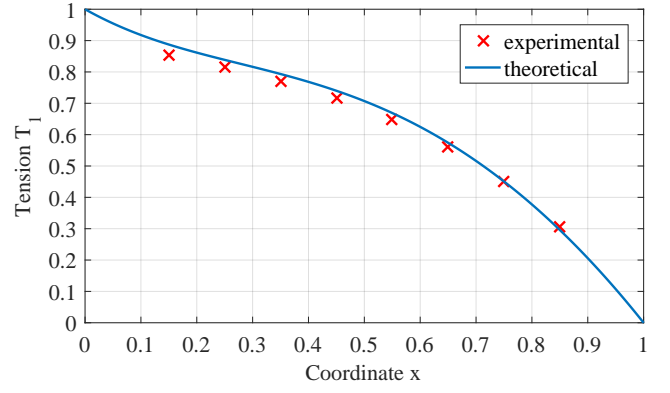


Fig. 15: Tension T_1 over the x axis, comparison between theoretical and experimental data ($d = 0.5$).

X. CONCLUSION

In this paper a new family of overhead travelling cranes, based on variable drums and named Cable-Based Robotic Crane, was presented. The direct kinematic analysis and the synthesis of the geometry of a variable radius drum were proposed. The VRD theory was applied firstly on a bi-dimensional horizontal moving mechanism and then to a three-dimensional overhead crane. An experimental prototype of a CBRC, produced using 3D printing technology, was presented and an analysis of tensions in cables was provided. Finally, the performance of this mechanism were evaluated and a deviation of the end-effector from the nominal position of less than 1%, throughout the whole working area in both x , y and z directions, was found. Furthermore, the cable tensions have been measured and compared with the theoretical values.

The presented prototype of Cable-Based Robotic Crane highlights the advantages of using VRDs with respect to traditional CDRs, the first and foremost being the simplicity in the required actuation system. In fact, it is well known that one would need several CRDs with a coupled actuation system to drive them in a synchronous manner in order to make the end-effector moving along a linear path on a planar surface. On the other hand, the VRD requires only to compensate the variation of the radius, in order to produce a demanded speed or torque output. Moreover, the CBRC here described is characterized by a lighter weight with respect to traditional overhead travelling cranes, it is reconfigurable and modular. It has to be noticed that, in this preliminary prototype, oscillation and vibration effects might occur during the end-effector motion. Even if this problem raises also in traditional overhead travelling cranes, in the presented experimental system the cables flexibility as well as the pendulum phenomena might introduce negative issues during the movement of the load. From a practical perspective, where stiffness might be required by several applications, this aspect need to be further investigate, e.g. by implementing anti-swing as well as vibration-suppression control strategies [23]. Furthermore, the maximum speed of the system depends on the size of the cables and their tensions, as well as its acceleration is limited by the cables stability, since they support traction

but no compression. Such problems have been addressed in other cable robots, where gravity forces are involved [44].

This research study has reached remarkable results in the application of variable radius drums to cable-based overhead cranes. Nevertheless, improvements can be done in the manufacturing of the complex shapes of VRDs profiles. Furthermore, a complete sensitivity analysis of CBRC kinematics would be useful to evaluate potential issues before providing interesting real applications. In future, we plan to further investigate cable-driven cranes based on VRDs. In particular, the safety of the system in the case of cable failure [45] can be analysed and the elongation of the cables [12] can be taken into account.

APPENDIX A

MATHEMATICAL DERIVATIONS OF THE VRD SYNTHESIS

In this appendix, the mathematical derivations of the VRD profile synthesis are reported.

For the further calculations, it is to be noticed that:

$$\frac{d\mathbf{T}(x)}{dx} = \mathbf{T}\left(x + \frac{\pi}{2}\right) \quad (27)$$

In particular, by differentiating Eq.(6) with respect to angle α , we can obtain:

$$\begin{aligned} \frac{d\mathbf{P}_t}{d\alpha} &= \frac{d\mathbf{T}(\alpha)}{d\alpha} \begin{Bmatrix} c_d \\ 0 \end{Bmatrix} + \frac{d\mathbf{T}(\alpha)}{d\alpha} \mathbf{T}(-\gamma) \mathbf{T}\left(-\frac{\pi}{2}\right) \begin{Bmatrix} l_t \\ 0 \end{Bmatrix} \\ &\quad - \frac{d\gamma}{d\alpha}(\alpha) \frac{d\mathbf{T}(-\gamma)}{d(-\gamma)} \mathbf{T}(\alpha) \mathbf{T}\left(-\frac{\pi}{2}\right) \begin{Bmatrix} l_t \\ 0 \end{Bmatrix} \\ &= \mathbf{T}\left(\alpha + \frac{\pi}{2}\right) \begin{Bmatrix} c_d \\ 0 \end{Bmatrix} + \mathbf{T}(\alpha) \mathbf{T}(-\gamma) \left(1 - \frac{d\gamma}{d\alpha}\right) \begin{Bmatrix} l_t \\ 0 \end{Bmatrix} \end{aligned} \quad (28)$$

The unit vector normal to the VRD profile in tangent point P_t is:

$$\mathbf{n} = \mathbf{T}(\alpha) \mathbf{T}(-\gamma) \begin{Bmatrix} 1 \\ 0 \end{Bmatrix} \quad (29)$$

Since $d\mathbf{P}_t/d\alpha$ points at any time along the tangent line $P_t P_b$, it is normal to unit vector \mathbf{n} . This orthogonality relationship can be written as:

$$\mathbf{n}^T \frac{d\mathbf{P}_t}{d\alpha} = 0 \quad (30)$$

By substituting Eq.(28) and (29) into Eq.(30) and by using the property of orthogonal matrices $\mathbf{T}^T \mathbf{T} = \mathbf{I}$, it follows:

$$\begin{aligned} \{1 \ 0\} \mathbf{T}^T(-\gamma) \mathbf{T}\left(\frac{\pi}{2}\right) \begin{Bmatrix} c_d \\ 0 \end{Bmatrix} + \left(1 - \frac{d\gamma}{d\alpha}\right) \{1 \ 0\} \begin{Bmatrix} l_t \\ 0 \end{Bmatrix} &= 0 \\ c_d \sin(-\gamma) + \left(1 - \frac{d\gamma}{d\alpha}\right) l_t &= 0 \end{aligned} \quad (31)$$

The relationship between the lever arm l_a , the unrolled cable length and the VRD rotation angle α is $l_a = dg/d\alpha$. In particular, from Fig.3 it can be easily seen that $c_d \cos(\gamma) = l_a$. By combining the two previous equations, we obtain $c_d \cos(\gamma) = dg/d\alpha$. At this stage, we can differentiate the

previous relationship and, by considering that $c_d \sin(\gamma) = \sqrt{c_d^2 + l_a^2}$, we obtain:

$$\frac{d\gamma}{d\alpha} = - \frac{\frac{d^2 g}{d\alpha^2}}{\sqrt{c_d^2 - \left(\frac{dg}{d\alpha}\right)^2}} \quad (32)$$

APPENDIX B

VRD SYNTHESIS BY CONSIDERING THE RADIUS OF THE IDLE PULLEY AND THE CABLE THICKNESS

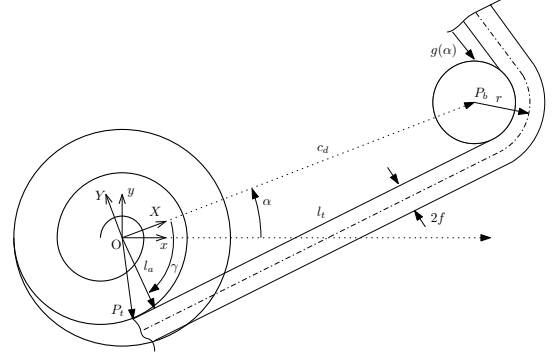


Fig. 16: Variable radius drum parameters by considering the radius of the idle pulley and the cable thickness.

In the following, we introduce the radius r of the idle pulley and the thickness of the cable $2f$. The radius r includes the radius of the idle pulley and half of the cable thickness. In Fig.16 a graphical representation of this configuration is reported. Similarly to what is stated in Eq.(6), the geometry of the VRD can be now expressed as:

$$\mathbf{P}_t = \mathbf{T}(\alpha) \begin{Bmatrix} c_d \\ 0 \end{Bmatrix} + \mathbf{T}(\alpha) \mathbf{T}(-\gamma) \mathbf{T}\left(-\frac{\pi}{2}\right) \begin{Bmatrix} l_t \\ 0 \end{Bmatrix} + \chi(\alpha) \quad (33)$$

where the function $\chi(\alpha)$ is equal to:

$$\chi(\alpha) = \mathbf{T}(\alpha - \gamma) \begin{Bmatrix} r \\ 0 \end{Bmatrix} - \mathbf{T}(\gamma + \alpha) \begin{Bmatrix} f \\ 0 \end{Bmatrix} \quad (34)$$

We can express the vector tangent to the profile in P_t as:

$$\begin{aligned} \frac{d\mathbf{P}_t}{d\alpha} &= \frac{d\mathbf{T}(\alpha)}{d\alpha} \begin{Bmatrix} c_d \\ 0 \end{Bmatrix} + \frac{d\mathbf{T}(\alpha)}{d\alpha} \mathbf{T}(-\gamma) \mathbf{T}\left(-\frac{\pi}{2}\right) \begin{Bmatrix} l_t \\ 0 \end{Bmatrix} \\ &\quad - \frac{d\gamma}{d\alpha}(\alpha) \frac{d\mathbf{T}(-\gamma)}{d(-\gamma)} \mathbf{T}(\alpha) \mathbf{T}\left(-\frac{\pi}{2}\right) \begin{Bmatrix} l_t \\ 0 \end{Bmatrix} + \frac{d\chi(\alpha)}{d\alpha} \\ &= \mathbf{T}\left(\alpha + \frac{\pi}{2}\right) \begin{Bmatrix} c_d \\ 0 \end{Bmatrix} + \mathbf{T}(\alpha) \mathbf{T}(-\gamma) \left(1 - \frac{d\gamma}{d\alpha}\right) \begin{Bmatrix} l_t \\ 0 \end{Bmatrix} \\ &\quad + \frac{d\chi(\alpha)}{d\alpha} \end{aligned} \quad (35)$$

since

$$\begin{aligned}
\frac{d\chi(\alpha)}{d\alpha} &= \frac{d\mathbf{T}(\alpha - \gamma)}{d\alpha} \left(1 - \frac{d\gamma}{d\alpha}\right) \begin{Bmatrix} r \\ 0 \end{Bmatrix} \\
&\quad - \frac{d\mathbf{T}(\alpha - \gamma)}{d\alpha} \left(1 - \frac{d\gamma}{d\alpha}\right) \begin{Bmatrix} f \\ 0 \end{Bmatrix} \\
&= \mathbf{T} \left(\alpha - \gamma + \frac{\pi}{2} \right) \left(1 - \frac{d\gamma}{d\alpha}\right) \begin{Bmatrix} r \\ 0 \end{Bmatrix} \\
&\quad + \mathbf{T} \left(\alpha - \gamma + \frac{\pi}{2} \right) \left(1 - \frac{d\gamma}{d\alpha}\right) \begin{Bmatrix} f \\ 0 \end{Bmatrix}
\end{aligned} \tag{36}$$

It has to be noticed that Eq.(35) is equal to Eq.(28). Consequently, the orthogonality condition of Eq.(30) leads to the same results of Eq.(8) and (9). In fact:

$$\mathbf{n}^T \frac{d\chi(\alpha)}{d\alpha} = 0 \tag{37}$$

Finally, we obtain that the geometry of the VRD profile, in Cartesian coordinates, is given by Eq.(33), associated with Eqs (8), (9) and (34).

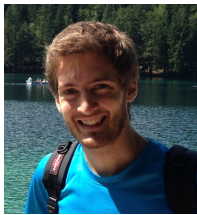
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