Conceptual Design and Simulation of Cable-driven Parallel Robot for Inspection and Monitoring Tasks

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Abstract. The paper deals with the conceptual design of cable-driven parallel robot which will be used for inspection and monitoring tasks in production process. The reason and need of vision based control of the production process is described in the introduction. Furthermore, mechanisms with parallel kinematic structure are described, as well as their usage in industry and sports broadcasts. On that basis, there is proposed the conceptual design of the cable driven parallel robot (CDPR) for desired task of visual monitoring of production line. Finally, there is proposed a simulation of designed robotic system and workspace shape analysis.

1 Introduction

The main effort of product companies is to ensure the high and stable quality of their products in order to be competitive. Saga et al. [1] mentioned that advanced digital technology is already used in industry, however with the concept of Industry 4.0 it transforms production into smarter automation in various ways through the installation of industrial and collaborative robots, intelligent sensors, advanced monitoring methods, the application of production simulations, virtual reality and virtual commissioning [2]. Modern advanced machine vision systems based on "smart camera sensors" have opened new applications and rapidly spread into many industrial areas, such as general process control, object identification and recognition, as well as quality control [3,4].

It is the implementation of advanced production monitoring systems at all its levels of production systems and especially in assembly operations that can have a significant positive impact on the final quality of the product. The beneficiary's conditions are increasingly checked during a quality audit led by his quality technicians directly on the production lines of the subcontractors [5]. The sub-contractor must demonstrate in the inspection documentation that the product is manufactured according to the needs of the receiver. This is necessary in identifying the causes of defects in the machining of the final product and analyzing the causes of defects in the products sold. Such an analysis also
provides advantages with information on the technical level of their subcontractors [5,6]. In this way, the customer can create databases of information about the entire production cycle of the product. This further allows, if necessary, to trace the specific process, operation, operator where the possible error occurred and thus implement corrective measures.

Nowadays, the manufacturing process places high demands on the quality and speed of production, with these demands the manufacturing process is susceptible to various factors. When building such monitoring or diagnostics systems [7], there can be used special tools and sensors to monitor the necessary control parameters, depending on the type of production, the monitored parameters, the required frequency of data acquisition and the method of evaluation.

The term quality contains two components that determine whether a product is fit for its use quality of product design and product quality in production. The production should produce a quality product with low costs and high labor productivity. Quality management in production therefore applies to:
- input control of material,
- production control,
- output control,
- inspection of work equipment,
- control metrological service.

On this basis, we have proposed the conceptual design of the cable-driven parallel robot (CDPR) for desired task of visual monitoring of production line, including simulation of designed robotic system and workspace shape analysis.

2 Visions systems

The purpose of manufacturing process control is to minimize the risk of before mentioned factors and eliminate the risk of production process shutdown. Nowadays, there are many ways to control and monitor the production process in order to avoid the occurrence of scraps or even to stop the production process. When monitoring and controlling the production process, it is possible to monitor various parameters affecting the operation process of the production line by means of vision based control [8]. For vision based control, it is possible to use static cameras located in the production line or a camera which moves in the space above the production line. For moving the camera in space a robot with a parallel kinematic structure should be used.

Vision systems are used in many industry areas. Their application can be successful in every process, where the evaluation of the product quality can be done with the use of sight, therefore in the product identification and product checking. Vision systems are used practically in every industry branch and also in such areas as medicine or meteorology. In industrial area of use we can also name [9]: motorization, food industry, electronics, pharmacy, medical goods, dentist needles, package manufacturing.

3 Parallel kinematics mechanism

A parallel kinematic structure is a mechanism with a closed kinematic loop, the structure consists a base, a platform, and at least two independent guide chains. The guiding chains are connected to both the base and platform as well. This definition is very open as it includes, for example, redundant mechanisms (mechanisms with a greater number of actuators than the number of controlled degrees of freedom - DOF) [10,11]. For this reason,
suitable criteria have been established to define which characteristics a mechanism must have in order to be considered as a parallel kinematic mechanism. According to Knoflíček, et al., the general parallel mechanism (or mechanism with parallel kinematic structure) in the field of manufacturing machines and industrial robots means any mechanism with the following characteristics [12]:

– it is composed of a base, a moving platform and guiding chains;
– the platform is supported by at least two independent guiding chains, each of them contains at least one simple actuator (an actuator that allows movement with minimum one degree of freedom);
– the number of actuators is equal to or higher than the number of end-effectors’ DOF;
– if the actuators are locked, the total output mobility is equal to 0.

In terms of the number of independent guide kinematic chains in a parallel mechanism, it is possible to define [13]:

– Fully parallel mechanism - a parallel mechanism with n-DOF of the end-effector connected to the base by n-independent guide chains, each having one simple actuator.
– Hybrid parallel mechanism - a parallel mechanism with n-DOF of an effector connected to the base by m-separate guide chains, each having one or more actuators.
– Orientational parallel mechanism - is a parallel mechanism for which all points on the moving platform are described by paths and all these paths are placed on concentric spherical surfaces.

The comparison of robots with conventional (serial) kinematic structure, as well as parallel kinematic structure (PKS) is shown in Fig. 1. Serial robots (Fig. 1a) are inspired by the structure and function of the human arm which consists of a series of joints and bones connecting the torso with the hand. Using the muscles as actuators, the hand can be freely moved in space to manipulate objects in the environment. For a robot as technical system, muscles and bones are replaced by links and actuated joints in order to mimic the human’s motion capacities. The overall kinematic chain is called serial, meaning that there is one unique sequence of links and actuated joints that create the desired motion. Serial robots are often referred to as robotic arms or articulated robots due to their kinematic similarity with the human arm. The other two figures (Fig. 1b and 1c) show the difference of a parallel robot with respect to a serial robot – there are visible additional kinematic chains to connect the end-effector with the base [14].

Fig. 1. Different robot architectures [14]: a) Industrial robots with serial kinematic structure, b) Stewart–Gough platform with PKS, c) delta robot with PKS.
4 Cable Drive Parallel Robot

Cable Drive Parallel Robot can be considered as a new mechanism, although its principle has been known since the 1990s when J. Albus and his team in the National Institution of Standard and Technology (NIST) project called RoboCrane constructed the parallel rope crane [14]. It was controlled by six ropes and had a triangular construction. Another project was the construction of the parallel crane DARTS SYSTEM used for unloading goods from a ship to a train which was used by August Cargo [10].

In Fig. 2 we can see basic concept and components of a cable-driven parallel robot with 8 haul ropes which are placed in each corner which contains mobile platform a fixed machine frame. The lengths of the cables (and sometimes also the positions where the cables are attached to the frame) are changed by an actuation system which is called winch for simplicity although there are other mechanisms for actuation. For most robots, the winches are fixed to the machine frame to simplify the electric connection with the power and control system [13].

**4.1 Use of a Cable-Drive Parallel Robot**

The biggest advantage of the cable-driven parallel robot (CDPR) is extremely low weight and adaptability for working with huge space. Due to low weight, the platform is able to move at extremely high dynamics – very high speed and acceleration of up to 40g (40-times gravity) which is even higher than the acceleration of delta robots (regularly about 15g) [15, 16].

The biggest disadvantage of the CDPR are the ropes themselves, the ropes don’t allow pressure on the platform. The robot is therefore not able to move in way the rope pushes the platform. For this reason, its necessary all the ropes must be under constant tension to secure the static of the platform in specific position in working space. The rope sagging is unacceptable and it would lead to positioning inaccuracies and possibility of vibrations occurrence [17] and finally to difficulties during winding.

Their usage of is still very rare. However, there are many potential applications for them. Practically, it is possible to deploy such kind of robot for any activity whose requirements will be appropriate to its capabilities (accuracy, speed, position availability, etc.). We will list the activities for which the rope robot has already been deployed and has successfully fulfilled its role [18]:

![Concept and structure of a cable-driven parallel robot; here is shown prototype of IPAnema 2, IPA Stuttgart, Germany [14].](https://example.com/image.jpg)
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- crane with a large working area (loading of goods on a ship, truck, ...);
- relocating objects;
- measure dimensions, distances and positions;
- flight and other simulators (octahedral arrangement of ropes);
- camera for sports broadcasts over stadiums;
- construction and painting of buildings, bridges, aircraft, ships, etc.

![Fig. 3. Workspace of CDPR.](image)

A basis workspace of CDPR can be represented by a virtual block. In Fig. 3 we can see a shape of working space of cable-driven parallel robot with 8 haul ropes which are placed in each corner.

4.2 Using a CDPR for video and monitoring tasks

One of the examples of using a cable-driven parallel robot is to use them to capture sports broadcasts over stadiums as the robot can work in a very large work area. Outstanding examples of under-constrained cable drive robot are the SkyCam [19] and SpiderCam systems (Fig. 4) used in many sporting arenas around the world. These systems provide computer controlled, stabilized, cable-suspended camera transporters. The systems are maneuvered through three dimensional space with a set of four computer controlled winches. Both static and dynamic active stabilizations of camera carriers that ensure proper camera orientation are included in the real time control system. The idea of SkyCam and SpiderCam can also be applied to engineering production where we can place a cable drive robot over the production line and by visual control we can monitor the production process and parameters of production by using a various sensors and probes placed on the platform.
5 Conceptual design of cable-driven parallel robot used for inspection and monitoring tasks

For our application of using a cable driven parallel robot for vision based control we have to create a conceptual design where will be the working space located above the production line. The working space is cubic shape of dimension 20x5x2m, in Fig. 5 in gray color we can see the space which is restricted for the production line. Robot working space is above the production line and its bounded from below by the manufacturing machines used in production and from the top is bounded by the construction of the production hall, respectively by the periphery dimensions of the robot construction. Usually in most of production halls are is a gantry crane used, that’s the reason why our winching device can’t be placed in corners of production hall. We have to design a construction made of metal profiles which will be placed around the production line.

Fig. 4. Cameras placed on platform, a) SkyCam system [19] b) SpiderCam system [14].

Fig. 5. The robot working space and construction made of metal profiles.
Our solution consists a metal profiles which makes up a self-supporting structure, whole production line and devices used in production are located inside in the structure, our solution offers possible movement of a robot over the entire production line.

5.1 Winch

The design of a winch machine is very important task in conceptual design and also for mechanical engineering, because winches are used in crane applications from their beginning. There are more possibilities to design the crane. One solution consists in use a winch drum with rope guidance and other with using a winch drum without rope guidance, as well as is possible to construct a winching device which can be winding a rope in one or more layers. A winch without a rope guidance is cheaper solution and also is possible to store more rope length in drum. This is an advantage we need for our application. But there are also a disadvantages. Using a winch without guidance result in reducing accuracy in estimating the length of cable as well as high wear of the cable.

In our solution we make a design of winch without guidance and also a design of wiring machine with guidance. In solution without rope guidance the will be used a drum with haul rope placed on the rotating platform. The rotating plate is connected to base plate by using axial bearings. In each top corner of construction will be placed rope winding assembly. The complete assembly consisting of a drum with haul rope, rope winding device which is a servo engine with transmission and as well as the pulley is shown in Fig. 6.

![Fig. 6. Rope winding assembly – first design.](image)

Our second design shown in Fig. 7 is a solution based on using a winch drum with rope guidance. Rope drum is powered by rope winding drive which is a servo motor connected to control computer. Haul rope will be stored on drum by the automatic rope guidance device.
5.2 Automatic wiring machine

When using a cameras and devices designed for monitoring task is necessary to connect a power and data cable to these devices. As is necessary these devices are placed in our effector. Basically, effector we are using is a plate stretched in between ropes where are placed cameras and other devices with required sensors, the installation and using of the sensors depends on the monitoring requirements which will be specifically monitored in the production process. On the effector is possible to place various types of devices, is possible to place a scanning device, air quality sensors, thermal camera, temperature sensors or it can be simple camera with live video transmission to the operator. This is the reason we need to get electric power to platform and get back data form devices used. For connecting the devices, we can use an automatic wiring machine. Our final design of a wiring mechanism is shown in Fig. 8. It is composed of winch drum, cable guidance, power and data supply.

Fig. 7. Rope winding assembly – second design.

Fig. 8. Design of an automatic wiring machine.
5.3 Effector

As we said in previous part, our effector is basically a metal plate stretched between haul ropes. On the bottom side of platform can be placed a camera with live video transmission to the operator. As well as various types of sensor for monitoring tasks of production process. The design of a robot effector is shown in Fig. 9.

![Camera platform](image)

Fig. 9. Camera platform.

The assembly with gimbal and industrial camera is necessary, because of the robot movement. While robot moving above the production line, is possible that the effector is making a little movement because of acceleration forces while changing the position. This moving is eliminated via camera gimbal. As well as is necessary to change the vision angle. Using a 3-axis gimbal allows to rotate around the center axles so it’s possible to scan required position of production line. Used parts are shown and described in Fig. 10.

![Assembly of a camera effector with 3-axis gimbal and industrial camera](image)

Fig. 10. Assembly of a camera effector with 3-axis gimbal and industrial camera.

5.4 Stretching forces in effector

For perform a stench analysis and calculating acting forces is necessary to know weight of effector equipped with gimbal and industrial camera[20,21]. On the created model, after
defining the material of each component it was found that the weight of the effector equipped with platform, four haul rope connectors, data and power connector, 6 screws but without industrial camera and gimbal is 3.352 kg. Weight of industrial camera and gimbal depends of used types. For calculating we use a weights of components which we found in their data sheets.

\[ m = m_{plat} + m_{cam} + m_{gim} \]  

(1)

\[ m = 3.352 + 0.325 + 0.550 = 4.227 \text{ kg} \]  

(2)

Where:

- \( m_{plat} \) – weight of platform (3.352 kg)
- \( m_{cam} \) – weight of industrial camera (0.325 kg)
- \( m_{gim} \) – weight of gimbal (0.550g)

To perform a stretch analysis of effector we also have to know the gravity force. The magnitude of the gravity force \( F_g \) acting at the effector center of gravity is:

\[ F_g = m \cdot g = 4.227 \cdot 9.81 = 41.467 \text{ N} \]  

(3)

We can see entire assembly of cable-driven parallel robot for inspection and monitoring tasks in Fig. 11.

\[ F_g = F_{g1} + F_{g2} + F_{g3} + F_{g4} \]  

(4)

\[ F_{g1} = F_{g2} = F_{g3} = F_{g4} \]  

(5)

\[ F_{g1} = F_g / 4 = 41.467 / 4 = 10.367 \text{ N} \]  

(6)
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We performed analysis in CAD software Creo Parametric 5.0. The results of moving platform structural analysis (Fig. 13) shows us that the stress is concentrated in joints between haul ropes and effector platform. That’s the most exposed place in platform.

Fig. 12. Simplified model of forces acting in robot effector.

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Fig. 12. Simplified model of forces acting in robot effector.

Fig. 13. Result of performed strength analysis on camera effector.

6 Conclusion

With increasing demands on the quality of production, the requirement to control the production process is increasing, this is the requirement why the production process must be monitored. In this paper we made a theoretical review of parallel robot’s usage for vision-based monitoring in production process. We analyzed a robot with a parallel kinematic structure and we selected a suitable type of parallel robot for the application in production process monitoring. As the most suitable type of robot we chose a cable drive parallel robot which we have described in the next part, we also have specified the possibilities of its use in sports and also in industrial applications. In the last part of the paper we created a simplified construction of cable drive parallel robot used for vision-
based monitoring of the parameters in the production process in the production line. The design itself consists of individual parts that can be used in the future when the robot will be build.

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