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Independent load carrying and measurement manipulator robot arm for improved payload to mass ratio

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A R T I C L E I N F O

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A B S T R A C T

Recently, the development of collaborative robots that have to work in a cooperative way with humans, has become an important trend both in academia and in the industry. Thereby, safety has increasingly become an essential research aspect. Today, the main techniques to ensure safety are based on reducing 1) the stiffness of the actuators and/or links, 2) the speed of the robot when it approaches humans or obstacles, and 3) the weight of the robot. In all these techniques, the robot's end-effector position is measured by position sensors on the joints, whereby the robot's limbs have to be as rigid as possible. This method has as possible drawbacks that the limbs have to carry unnecessary load (i.e. the robot's weight), and that the position errors increase with increased payload so that the robot can only be used for low payloads. To tackle these problems, we proposed a novel error compensation method based on the use of an additional measurement arm in parallel with the main load bearing arm, whereby the two arms are only coupled between the base and the end-effector. We designed a proof of concept robotic arm and validated the feasibility of our method. This paper presents the *End-Effector Position Measuring* (EEPM) method and introduces the *Independent Load And Measurement Arm* (ILAMA) to demonstrate the EEPM concept. With this novel method, the robot can be designed by strength instead of by stiffness. As a consequence, the weight of the limbs can drastically be reduced and the payload to mass ratio can be increased to a value that is bigger than one, while preserving the high end-effector position accuracy, as shown in the experiments. These advantages make the EEPM method very promising to use in collaborative robots or in mobile robot arms. Future works will investigate the feasibility of the proposed concept for real industrial robots with 6 to 7 DOF.

1. Introduction

During the last decades, industrial robots have become common in industry. Up till now, these robots are designed under the assumption that they operate in protective cages or non-physical safeguards [1], and as such are separated from human workers. For several economic reasons; e.g. quickly varying production processes, small batch size production in small and medium enterprises, and tasks with a higher complexity, there is an increased interest in collaborative robots [2]. These collaborative robots, the so-called cobots, will have to work in a cooperative way with humans, whereby they will have to share their workspace with the human workers and will possibly have to physically interact with them [3,4].

Since safety is the primary concern on the workfloor, the current industrial robots have to be adapted so that they will behave gently and safely nearby their human co-workers. Thereby, novel ISO safety standards and safety evaluation methods have to be taken into account [5–7]. However, these safety criteria are incompatible with the rigid, fast and heavy industrial robots we know today [8]. Therefore, three different main approaches were found by researchers to create these human friendly robots.

The first technique is based on *reducing the stiffness of the actuators or of the links*. Since the development of series elastic actuators [9], Variable Impedance Actuators (VIAs) [10] are richly investigated with pioneering work on the role of compliance for safety [8,11]. Dedicated control algorithms based on torque control have been developed to exploit the capabilities of these actuators [12–14]. Torque and energy efficiency can be improved by the use of e.g. parallel springs and locking mechanisms [15–18]. On the other hand, researchers try to make cobots safer, by using more compliant links; e.g. stiffness-controllable links that are pneumatically actuated of which the stiffness can be changed by varying the pressure inside the structure [19], and

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variable width compliant links [20].

The second technique is based on *reducing the speed of the robot*. As a consequence, the robot gets the time to change direction in the case that a collision is about to occur, and the impact of the collision is reduced in the case a collision is unavoidable [21]. Obstacles and humans can be detected by sensors as artificial skins with integrated cushioning elements [22], and depth cameras [23].

The third technique is based on *reducing the weight of the robot*. Generally, the high positioning accuracy requires high stiffness at the price of high robot mass relative to its payload. By using more advanced and lightweight materials, e.g. aluminum and composites reinforced with carbon fibers to replace heavy cast iron parts, the mass of the robot can be reduced from a payload to mass ratio of typically 1/10 for classical industrial robots to a ratio of 1/1 for the DLR-LWRIII lightweight arm [24]. Moreover, to increase the reliability of the commercial collaborative robot, the Kuka LBR IIWA 7 and 14 had to be reduced respectively to 1/3,5 and 1/2. This was also the case for other commercialized cobots like Universal Robots (1/3,5) and Baxter (1/10). Reducing the weight of a robotic manipulator is also a very important aspect for cobots that are placed on drones for aerial manipulation [25], and on mobile ground platforms.

In all these techniques, the same principle is used to calculate the robot's end-effector position and to perform the control, i.e. by position sensors on the joints whereby the robot's limbs have to be as stiff as possible to obtain a high accuracy. This traditional method has two major drawbacks: the limbs have to carry unnecessary load since they have to be very stiff, and the position errors increase with increased payload. The latter is due to the fact that the deformation in the load bearing structure, caused by the payload, cannot be measured. These two drawbacks give limitations in the design of robotic manipulators that use this measurement principle.

In [26] an error compensation method is proposed to improve the absolute positional accuracy of industrial robots without changing the way of designing a robotic arm. However, to tackle not only the problem of the position errors, but also the problem of the stiff and so very heavy design of the robot limbs, we propose another error compensation method, the *End-Effector Position Measuring* (EEPM) method. For this method, we use an additional measurement arm in parallel with the main load bearing arm. This measurement arm is only coupled to the load bearing arm at its base and end-effector and so, can measure the end-effector position without being coupled to the main load. The load bearing arm on its turn, can be designed on strength instead of on stiffness, since it only has to carry the load and does not anymore have to measure the position. With this paradigm, we move away from the traditional premise of good industrial robotic design that states *the stiffer the better* when it comes to the mechanical interface between motors and loads [27].

This paper is organized as follows. Section 2 discusses the novel EEPM concept. Section 3 introduces the proof of concept robotic arm, called the *Independent Load And Measurement Arm* (ILAMA). Section 4 presents the experiments on ILAMA that are performed to validate the feasibility of the EEPM concept and to explain the advantages (e.g. an improved payload to mass ratio) by using the EEPM method. Section 5 ends the paper with some conclusions and future perspectives.

2. End-Effector Position Measuring (EEPM) concept

To measure the end-effector position of a robot arm, traditional methods measure the position of the different joints. This has as a major drawback that the position accuracy is affected by the load carried by the robot arm, since the limbs (of which the load bearing arm is composed) will bend due to the load. To solve this problem, the EEPM method proposes to use an additional measurement arm. This arm is placed in parallel with the load bearing arm and is coupled to it at its base and end-effector, as depicted in Fig. 1.

Instead of having one robot arm that accomplishes two tasks, i.e. carry the load and measure the end-effector position, in the EEPM method the two tasks can now be divided over the two parallel arms. On the one hand, the additional measurement arm measures the end-effector position without being coupled to the load, whereby its position accuracy is not affected by an increasing load that causes bending of the compliant robot's limbs. On the other hand, the load bearing arm only needs to be strong enough to carry the load and so, does not need to be as stiff as possible anymore. As a consequence, the robot arm can be *designed by strength* (i.e. necessary to carry the load) instead of *by stiffness*. The principle of the method is visualized in Fig. 2.

The Kelvin (4-wire) Resistance Measurement is the electrical analogy of this mechanical concept. When measuring the resistance in a wire with long wires, the influence of the current through the wires disturbs the measurement itself (similar to the load on the arm deforming the limbs and as such disturbing the measurement); the solution here is to use independent wires, which are parallel to the current wires, to measure the voltage which is not loaded with the current. Similarly, in the EEPM concept, a second independent measurement arm, not loaded with the payload, is placed in parallel with the load bearing arm.

By using this novel concept, a large weight reduction can be obtained. To estimate this weight reduction, a structural analysis with a force of 100 N is performed on a simple hollow tube made out of steel with a length of 1000 mm and an outer diameter of 150 mm. For the conventional robots, a maximal displacement of 0.0025 mm is used (in order to achieve the stiffer the better paradigm, 1 order of magnitude smaller than the standard accuracy), whereas for the new concept a deformation is allowed, since it can be compensated by the measurement arm. Thus, a deformation of 0.025 mm (10 times bigger than the deformation of the conventional robots) can be used. The results of the finite element analysis are the following:

1. conventional stiff robot limb: minimal wall thickness = 45 mm, weight = 116.5 kg;
2. novel concept with compliant robot limb: minimal wall thickness = 2 mm, weight = 7.3 kg.

This result shows that the novel approach on position control of robotic arms is associated with a *massive weight reduction* of the structural elements of the robot. In this theoretical example a weight reduction with a factor of 16 can be achieved. In this case, the weight of the motors, bearings, and sensors are not taken into account. The weight of the motors in most commercial robots is around 10% of the total weight of the robot.

In this paper, we do not target complete soft continuum robot arms, e.g. inflatables with rubber-like materials or self-healing polymers as in [28–32]. The drawback of the latter examples is that their accuracy is not sufficient enough to reach what is required in several industrial applications. As presented in [33], the Young's Modulus is only defined for homogeneous, prismatic bars that are subject to axial loading and small deformations, but it is also argued that the Young's Modulus is nonetheless a useful measure of the rigidity of materials used in the fabrication of robotic systems [34]. Materials used traditionally in robotics to create rigid robot limbs, e.g. metals and hard plastics, have moduli on the order of 10^{10}–10^{12} Pa. In contrast, materials used in soft robotics are similar to natural organisms, often composed of soft materials, e.g. skin and muscle tissues, with moduli on the order of 10^{4}–10^{9} Pa. The Young's Modulus targeted for the EEPM concept is in between the soft robotics and rigid robotics and lies around 10^{10} Pa [33].

3. Proof of concept

The aim of this section is to demonstrate that by abandoning *the stiffer the better* paradigm for the limbs and by focusing the design on the required *strength* to carry the payload, the weight of the limb can be