Analysis of the quasi-stability of kinematic parameters for manipulators system during the docking process using the Digital Twin approach

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Abstract. This study analyzes the acceleration of the arms of a dual system of manipulators that aim to achieve the minimum distance by mimicking the process of approaching spacecraft that are trying to connect. The research was performed simultaneously on a real model and its digital equivalent, in accordance with the Digital Twin (DT) approach. The obtained acceleration values show, for some set sampling times, read out positions and velocities, separate distributed regions of achievable values.

1. Introduction

Digital Twin (DT) technology has attracted a great deal of interest in recent years in many projects, including automation and robotics industry [1-18]. This is the result of the progressive digitalization of production processes combined with the increasing use of artificial intelligence methods [19-24], the processing of large amounts of data [25-29] in real time, and the implementation of decision-making systems [30-34].

One of the quantitative measures of the prevailing trends can be the study of the state of the art, e.g., using available patent databases, such as the European Patent Office Espacenet [35]. Figure 1a shows the number of granted patents with the keywords “digital twin model” in the years 2002-2019. The visible trend is increasing, but at the same time it shows the initial level of development of this new technology – the number of granted patents is relatively low. On the other hand, scientific publications are already at a higher level, the number of which has approximately doubled in recent years, as shown by the Web of Science (Fig. 1b), demonstrating the growing interest in this topic. Nevertheless, this relatively new field of technical activity requires further research and implementation in universities and industry.
The term “Digital Twin”, referred to in this article, is often used inappropriately according to the situation. First, the issue of creating a digital model that mirrors a physical one involves an important element—the question of whether the created model is coupled to its real counterpart by a suitable interface. Secondly, the issue is whether this coupling of data delivery is unidirectional or bidirectional [36]. In the simplest situation we have been dealing with since the beginning of the development of modern science, the model invented by standard mathematical methods is quantitative and is called a digital model (DM), which means that it does not communicate with any real device or physical system. In the next step of science development, a coupling between the model and the real arrangement was included—the data of the real object can be automatically transferred to its digital counterpart, allowing imitating the real situation. In this case, we can speak of a Digital Shadow (DS) approach. In its most advanced form, when a digital model can automatically influence the state of a physical system, we speak of Digital Twin (DT) technology—information and control take place in both directions; from model to reality and vice versa.

Therefore, the present work refers to the DT type approach classified above. More precisely, the article presents partial results of research on a system of two x-y-z manipulators whose working ends must connect while moving in three-dimensional space. The process of connecting or docking is combined with analysis of the image of the object fed from one of the manipulators by a camera mounted on the tip of the other manipulator. The paper presents the results of the docking process simulated from the point of view of the recorded accelerations of the dual system arms. We consider two basic stages of the approach; the initiation stage (objects are far away) and the final stage (objects are at a minimum possible distance). For given various lengths of averaging times of kinematic data, we obtain an interesting phenomenon of formation of separate subsets of acceleration values that guarantee maintenance of the minimum distance. The presented system, together with the implemented image analysis, mimics the docking process in satellite and space technology [37–42] and may be suitable for other automatic approach processes, e.g., in atomic force microscopy.

2. Constructed tandem set of robotic manipulators

The designed and built experimental system is shown in Fig. 2. The manipulator arms are controlled by stepper motors and the whole solution is similar to 3D printers. The joint influence area of the manipulators covers a region of 0.25 m x 0.25 m x 0.25 m. The digital part was implemented in the CoppeliaSim environment [43] using the Lua language [44]. The communication between the real and the digital part takes place using a joystick connected to an Arduino microcontroller. The implementation of the DT technology requires the implementation of simple and inverse kinematics for the 3-axis Cartesian robots.

In the next part of the description, we report on the analysis of accelerations and the associated analysis of the force sensor. The force sensor tip presses on a small plate mounted at the second robot

![Figure 1. (a) Patents and (b) publications registered in recent years, searched with the keywords “digital + twin + model” in the Espacenet database and the Web of Science, respectively.](image-url)
arm. When the observed force values, both in the real and virtual systems, fall within a certain range, the docking process is complete and optimized. In addition, it is important to keep the system in the coupled state within a certain period of time. The continuously calculated accelerations of the coupled system are not constant, but show characteristic instabilities, which we believe have significant practical consequences.

**Figure 2.** The designed and constructed set of tandem manipulators – the real part of the Digital Twin approach (left panel), the virtual representation of the Digital Twin model (right panel).

3. **Analysis of docking phase from the point of accelerations**

The docking process consists of continuous measurements (in a real system) or continuous calculations (in a digital model) of the acceleration value of the manipulators. One of the manipulator arms has a force sensor, as mentioned above (Figure 3). On the basis of the measured value of the force, the acceleration values $a = F / m$ are determined and compared with the values of the accelerations calculated on the basis of the kinematic data – as we know, the acceleration is the first-time derivative of the speed or the second time derivative of the position. However, it should be emphasized that the notion of derivative of a function is an abstract concept, determined for infinitely small changes in position and the corresponding infinitely short time intervals. In laboratory and industrial reality, we are dealing with measurable, finite displacements and time intervals. In other words: In the real world, we are dealing with average values. The unit of time for calculating the approximate (averaged) derivatives can be then treated as the measured sampling time.

**Figure 3.** The force sensor implemented in the digital part of the experimental system. It was taken from the CoppeliaSim simulator. It is able to measure deformations, forces and torques. The small plate at the end of the sensing cylinder is used to bias very small, non-zero deformation.
In the final stage of the docking process, the acceleration values determined from the measured values of the force sensor are compared with the kinematically calculated numerical values. If these values are comparable, the docking process is complete and the connected manipulators are in a quasi-stable state characterized by a minimum distance (Figure 4).

The linked state, understood in this way, may exhibit instabilities that manifest themselves as continuous fluctuations of the connected system about the equilibrium position, described in our case by fluctuations in the acceleration values. In a real device, e.g., a satellite docked to a base space station, the docking process continues using a permanent mechanical connector. From this point of view, the solution presented here describes the phase of docking in which a spacecraft approaches a minimum distance before the final stable connection is established.

An interesting phenomenon discovered in the present work is the existence of various quasi-stability regimes of the system. The most striking one seems to be the formation of a kind of admissible band values of the kinematic parameters, the occurrence of which depends on the sampling frequency of the data in the time domain (Figure 4).

Figure 4. Numerical values of the z-axis component of acceleration (vertical direction of the system) calculated for different sampling times: (a) 10 ms, (b) 25 ms, (c) 100 ms; and (d) the numerical results for the x-axis component of the acceleration (direction along the horizontal distance between the manipulators) calculated at 50 ms sampling time. For the cases a, b, and c, the minimum distance was achieved after approx. 5 s, while for case d, the minimum distance was reached after 20 s.

4. Summary
The paper presents the results of simulations of kinematic parameters of a manipulator system performing the approach to the minimum distance related to a docking process. Interesting effects were found, such as the formation of separate bands of acceleration values in the digital model of the system, which is an equivalent of the real system, realized in the Digital Twin approach. It should be emphasized that very precise electro-mechanical elements were implemented in the model, especially the drive
transmission system with ribbed belts and stepper motors. The obtained results allow capturing the instability of kinematic parameters of real objects under industrial conditions. This approach therefore has very important practical consequences. It can contribute to the early prediction and detection of failures, based on the analysis of the dynamics of a digital model in conjunction with its real counterpart.

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