Abstract

The aim of this article is to present an overview of the most important robotic processes in which force control methods are applied. In recent years, robotization has seen a rapid increase in the use of industrial robots in tasks that require simultaneous implementation of a given path of motion and the robot’s force of interaction with the environment. In the field of industrial applications, this applies to issues related to the robotization of machining or some assembly tasks, but also the complex issue of cooperation between robots and people. One of the first applications of force control systems in robots were machining tasks such as grinding or blunting of sharp edges. Currently, robots are used in the following types of machining: grinding, polishing, chamfering, blunting, light milling. The implementation of such tasks requires the use of so-called position-force hybrid control. The task of such a control system is to implement the desired trajectory of the tool movement along the edge being machined or on the machined surface and to exert an appropriate clamping force of the tool. In the field of robotic machining, an important and still valid issue is the development and implementation of control strategies that ensure the quality of the mechanical machining process of the part despite the occurrence of unmolded phenomena, caused by, for example, significant errors in the geometry of the parts with local surface disturbances or its flexibility.

Another of the basic applications of force control systems in robots are assembly tasks. In such processes, force control is particularly important, because too high interaction forces between the assembled components lead to large distortions and prevent the correct process from running. There are many papers in the literature that describe the problem of monitoring the machining process using force sensors. Monitoring the machining process is important in the industrial production of parts with a high unit cost. Any irregularity in the production of the part causing its non-compliance with the documentation is a cause of significant financial losses. Process monitoring aims to prevent irregularities during its implementation and to correct or discontinue the machining process.

Friction stir welding is a method of joining materials without using consumable materials and without melting materials. In the process of friction stir welding, a cylindrical tool with a mandrel performs a rotary motion and at the same time is slowly moved along the joint area with simultaneous clamping. An industrial robot is responsible for the movement along the joint. The friction welding process is very sensitive to the temperature in the joint area. The temperature is not controlled directly, but by three other parameters: tool feed speed, tool speed and tool clamping force. For this reason, robots used for friction welding are equipped with position-force hybrid control systems. In recent years, the issue of cooperation in the human-robot system has become more and more important. The main area of application of this approach is assembly tasks. This solution has a number of advantages, such as the possibility of using the lifting capacity of the robot to lift heavy objects and the “ingenuity” of a human to maneuver the object. The robot, thanks to force sensor, is able to detect the method of maneuvering an object desired by a human.

Summing up, it can be said that the use of force control has significantly increased the functionality of robotic systems in recent years.

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Introduction

In recent years, robotization has seen a rapid increase in the use of industrial robots in tasks that require simultaneous implementation of a given path of motion and the robot’s force of interaction with the environment. In the field of industrial applications, this applies to issues related to the robotization of machining or some assembly tasks, but also the complex issue of cooperation between robots and people. Effective implementation of robotic processes is closely related to the methods of measuring interaction forces in the robotic manipulator-environment system. In the literature on measuring the interaction forces of industrial robots with the environment, various approaches can be found. In one of them, the force of interaction is determined as the product of the assumed rigidity of the environment and its deformation, the deformation being determined on the basis of measurements of the position of the robot’s tip [1,2]. Currently, this method is practically not used. Nowadays, with the development of measurement systems in mind, a more beneficial approach is based on direct measurement of forces / moment forces using a sensor placed in the end-effector [3,4] (Figure 1). This way of determining the force does not require the adoption of an environment model, which, like every model, is burdened with errors and uncertainty of modeling. During the movements of the working tip with accelerations a certain disadvantage of such a solution is revealed; that is, the measurement of interaction forces is then disturbed by components coming from forces of inertia. In most processes, due to low accelerations, these disturbances are insignificant. In the case of high significance of forces of inertia, one can use methods of correcting of force sensor readings [5].

There is also an intermediate solution [6], which consists in determining the moment forces in the joints of the robot arm (based on measurement of motor current) and determination of forces in its tip using Jacobians known from kinematics (Figure 1). This requires the implementation of kinematics equations, the measurement of the current position of the arm and the calibration of its kinematic parameters. It is therefore an extremely complicated method.

The latest solution used in collaborative robots is to place a force sensor in the robot’s base (Figure 1), which makes it possible to detect a collision between a robot arm and a human, which is not always possible if a force sensor is placed in the robot’s end-effector. On the basis of work [3], it can be concluded that the majority of modern robotic manipulators with force control packages are based on force measurement by means of sensors placed in the working tips or base, and less frequently in joints. In the further part of the article, selected technical aspects of robotization of processes are presented, in which the functionality of robots to have the ability to measure the forces of interaction with the environment plays a special role. Paper presents the possibilities of using industrial robots for tasks such as: machining, assembly tasks, monitoring the machining process, friction welding, and robot-human cooperation.

Applications of Force Control Systems in Industrial Processes

Machining

One of the first applications of force control systems in robots were machining tasks such as grinding or blunting of sharp edges. Currently, robots are used in the following types of machining: grinding, polishing, chamfering, blunting, light milling. The implementation of such tasks requires the use of so-called position-force hybrid control [7–9]. The task of such a control system is to implement the desired trajectory of the tool movement along the edge being machined or on the machined surface and to exert an appropriate clamping force of the tool. Currently, industrial robotics has two principal hybrid position-force control strategies in robotic machining processes [10]. The first consists in maintaining the given interaction force at a constant speed of movement, whereby the path of movement is automatically adjusted to the shape of the contact plane (Figure 2). This method gives good results in applications such as polishing, when there is no significant loss in the machined surface, and the tool has a large active surface. The second control strategy [10] is based on the movement of the robot’s tip along the programmed path regardless of the shape of the surface being machined (Figure 2). The variable value is the speed of movement, which depends on the resistance to movement. In this strategy, the pressure force is not a controlled quantity. It depends on the assumed motion path and the actual shape of the contact surface. Sometimes the basic control strategies are modified in commercial solutions in order to introduce some flexibility in their implementation [11].
In the field of robotic machining, an important and still valid issue is the development and implementation of control strategies that ensure the quality of the mechanical machining process of the part [12] despite the occurrence of unmodeled phenomena, caused by, for example, significant errors in the geometry of the parts [13] (associated with the uncertainty of their position relative to the robot) with local surface disturbances [14] or its flexibility [15].

**Assembly Tasks**

Another of the basic applications of force control systems in robots is assembly tasks. In the first uses of assembly applications, pliable grippers with susceptibility were used to ensure high tolerance of the movement accuracy of a robot’s arm. Such systems were gradually replaced or supplemented with systems with force control [16,17]. This approach allows the avoidance of blocking components during assembly, checking the clamping pressure of the assembled components to avoid overloading, or detecting a mismatch of components due to incorrect fitting—too tight or loose. The robotization of the assembly of flexible components, as described in [18,19] is a particular challenge. In such cases, force control is particularly important, because too high interaction forces between the assembled components lead to large distortions and prevent the correct process from running.

**Monitoring of the Machining Process**

Monitoring the machining process is important in the industrial production of parts with a high unit cost. Any irregularity in the production of the part causing its non-compliance with the documentation is a cause of significant financial losses. Process monitoring aims to prevent irregularities during its implementation and to correct or discontinue the machining process. Process monitoring involves observing (measuring) sizes in the process in a direct or indirect way. In the case of machining, the aim of which is to achieve the appropriate geometric dimensions or surface roughness, direct measurement of these quantities is not possible during the process. Therefore, signals related to phenomena accompanying the treatment process are monitored. These accompanying phenomena are, for example, vibrations, noise, cutting forces or heat generation (Figure 3). These phenomena can be quantified using signals such as accelerations, acoustic pressure, interaction forces or temperature. Irregularities in the implementation of the process cause a discrepancy between the levels of measured values associated with the accompanying phenomena and reference levels for those quantities determined for the correctly carried out process.

The problem of monitoring the machining processes carried out with the use of tools with high rigidity, such as drills, files or cutters, is known in principle. Processing with such tools results in accompanying phenomena that are very “explicit”, and in the case of a disruption in the process the change in accompanying phenomena is significant and the disorder can be easily diagnosed. There are many papers in the literature that describe the problem of controlling the machining process using robotic force sensors. Numerous works describe the monitoring of the process of robotic polishing [20], grinding [21] or milling [22] using a signal from a force sensor.

**Friction Welding**

Friction stir welding is a method of joining materials without using consumable materials and without melting materials. In the process of friction stir welding, a cylindrical tool with a mandrel performs a rotary motion and at the same time is slowly moved along the joint area with simultaneous clamping. An industrial robot is responsible for the movement along the joint. As a result of friction of the tool on the joined components, heat is generated, and the surfaces of the joined components are brought to the yield point. The rotating tool causes the material to mix along the joint. After passage of the tool, the material cools down creating a permanent connection. Friction stir welding is used for joining components from the same materials, such as steels [23], aluminum alloys [24], metal matrix composites [25], but also materials of different types, such as steel with aluminum [26]. The friction welding process is very sensitive to the temperature in the joint area. The temperature is not controlled directly, but by three other parameters: tool feed speed, tool speed and tool clamping force. For this reason, robots used for friction welding are equipped with position-force hybrid control systems [7, 15].

The friction welding process can be disturbed by deformations of the welded components under pressure or inaccuracy of the path followed by the robot. For this reason, the works [27, 28] analyze the impact of these disturbances on the welding process and looks for ways to eliminate them. Another disturbance may be unevenness of the surface of the welded components, which can be compensated for by adjusting the clamping force. For this reason, the process of friction welding of components with complex curvatures is carried out using robotic stations [27, 29, 30], where it is possible to control the required process parameters and to implement complex trajectories, and not on CNC machines. Due to the advantages, this method is used in many industries: e.g. aviation [31], automotive [27], means of transport [32].

**Robot-Human Collaboration**

In recent years, the issue of cooperation in the human-robot system has become more and more important. Collaborative robots are commonly called cobots [33-35]. The main area of application of this approach are assembly tasks [36, 37] and small parts handling and inspection tasks. This solution has a number of advantages, such as:
1. The possibility of tasks being carried out by humans that are extremely difficult to algorithm and program while other tasks are carried out by the robot.

2. The possibility of using the lifting capacity of the robot to lift heavy objects and the “ingenuity” of a human to maneuver the object - thanks to force sensor; the robot is able to detect the method of maneuvering an object desired by a human [38].

This approach, however, brings with it the need to ensure the safety of the human. The ISO/TS 15066 technical specification prepared in 2016, which complements the two-part ISO 10218-1 and 2 standards, defines guidelines for industrial applications in which human and robot collaboration occurs. Of the four types of cooperating installations, two of them require the use of force / moment sensors. The first is a system in which hand-guiding is used. The robotic system is controlled by the operator by direct manual control [39]. The robot recognizes the desired direction of movement by measuring the forces applied to the arm. The second case is a system in which the robot and the human are working at the same time, and the force and speed of the robot’s arm movement are controlled and limited in such a way that the robot does not cause the human pain or injury while they are interacting with it.

**Conclusion**

The article presents an overview of robotic processes that can be implemented by robots equipped with a force control system. This functionality significantly extends the possibilities of robot applications. The wide possibilities of robots equipped with force control systems favor the integration of many processes in a single station, without the need to use several devices or a robotic cell. In turn, the lack of force control systems completely prevents the implementation of some of the presented processes, and in the case of others, leads to a decrease in quality, or forces the necessity of using additional devices, which reduces the economic value of the solution. The development of robotic applications in recent years has been possible thanks to equipping robots with sensor systems. In addition to vision systems, it was the force measurement and control systems that made it possible to expand the applications of robots in industry by enabling controlled interaction with the environment. In the future, it is expected the development of collaborative robots in industry as well as in services and everyday life.

**Conflicts of Interest**

The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

**References**

1. Wu Y, Chen S. Adaptive Neural Motion/Force Control of Constrained Robot Manipulators by Position Measurement. 2011 Seventh International Conference on Natural Computation. 2011;1:498-502.

2. Ohishi K, Miyazaki M, Fujita M, Ogino Y. Hybrid Control of Robot Manipulator without Force Sensor. IFAC Proc. 1993;26:991-996.

3. Marvel J, Falco J. Best Practices and Performance Metrics Using Force Control for Robotic Assembly. National Institute of Standards and Technology. 2012.

4. Cherubini A, Navarro-Alarcon D. Sensor-Based Control for Collaborative Robots: Fundamentals, Challenges, and Opportunities. Front Neurorobot. 2021;14:113.

5. Gierlak P, Burghardt A, Szybicki D, Kurc K. Eliminating the Inertial Forces Effects on the Measurement of Robot Interaction Force. Lect Notes Electr Eng. 2019;548:67-76.

6. Murakami T, Yu F, Ohnishi K. Torque Sensor less Control in Multidegree-of-Freedom Manipulator. IEEE Trans Ind Electron. 1993;40:259-265.

7. Gierlak P. Hybrid Position/Force Control in Robotised Machining. Solid State Phenom. 2014;210:192-199.

8. Gierlak P. Hybrid Position/Force Control of the SCORBOT-ER 4pc Manipulator with Neural Compensation of Nonlinearities. Lect Notes Comput Sci. 2012;7268:433-441.

9. Muszyńska M, Burghardt A, Kurc K, Szybicki D. Verification Hybrid Control of A Wheeled Mobile Robot and Manipulator. Open Eng. 2016;6:64-72.

10. Application Manual. Force Control for Machining. ABB Robotics. 2011.

11. Lotz M, Bruhm H, Czinki A. A New Force Control Strategy Improving the Force Control Capabilities of Standard Industrial Robots. J Mech Eng Autom. 2014;4:276-283.

12. Bruhm H, Czinki A, Lotz M. High Performance Force Control – A New Approach and Suggested Benchmark Tests. IFAC-Papers OnLine. 2015;48:165-170.

13. Pliego-Jiménez J, Arteaga-Pérez MA. Adaptive Position/Force Control for Robot Manipulators in Contact with a Rigid Surface with Uncertain Parameters. Eur J Control. 2015;22:1-12.

14. Gierlak P. Combined Strategy for Control of Interaction Force between Manipulator and Flexible Environment. J Control Eng Appl Informat. 2018;20:64-75.

15. Gierlak P, Szuster M. Adaptive Position/Force Control for Robot Manipulator in Contact with a Flexible Environment. Robot Auton Sys. 2017;95:80-101.

16. Roveda L, Pedrocchi N, Beschi M, et al. High-Accuracy Robotized Industrial Assembly Task Control Schema
with Force Overshoots Avoidance. Control Eng Practice. 2018;71:142-153.

17. Kramberger A, Gams A, Nemec B, et al. Generalization of Orientation Trajectories and Force-Torque Profiles for Robotic Assembly. Robot Auton Sys. 2017;98:333-346.

18. Lee DH, Na MW, Song JB, et al. Assembly Process Monitoring Algorithm Using Force Data and Deformation Data. Robot Comput.-Integr Manuf. 2019;56:149-156.

19. Heyn J, Gümbel P, Bobka P, et al. Application of Artificial Neural Networks in Force-Controlled Automated Assembly of Complex Shaped Deformable Components. Procedia CIRP. 2019;79:131-136.

20. Pilný L, Bissacco G. Development of on the Machine Process Monitoring and Control Strategy in Robot Assisted Polishing. CIRP Annals. 2015;64:313-316.

21. Pandiyen V, Caesarendra W, Tjahjowidodo T, et al. In-Process Tool Condition Monitoring in Compliant Abrasive Belt Grinding Process Using Support Vector Machine and Genetic Algorithm. J Manuf Proc. 2018;31:199-213.

22. Sugita N, Nakano T, Nakajima Y, et al. Dynamic Controlled Milling Process for Bone Machining. J Mater Process Technol. 2009;209:5777-5784.

23. Thomas WM, Threadgill PL, Nicholas ED. Feasibility of Friction Stir Welding Steel. Sci Technol Weld Joining. 1999;4:365-372.

24. Callegari M, Forcellese A, Palpacelli M, et al. Robotic Friction Stir Welding of AA5754 Aluminum Alloy Sheets at Different Initial Temper States. Key Eng Mater. 2014;622:540-547.

25. Guo J, Gougeon P, Nadeau F, et al. Joining of AA1100–16 Vol.% B4C Metal Matrix Composite Using Laser Welding and Friction Stir Welding. Can Metall. 2012;51:277-283.

26. Watanabe T, Takayama H, Yanagisawa A. Joining of Aluminum Alloy to Steel by Friction Stir Welding. J Mater Process Technol. 2006;178:342-349.

27. De Backer J, Christiansson AK, Oqueka J, et al. Investigation of Path Compensation Methods for Robotic Friction Stir Welding. Ind Robot. 2012;39:601-608.

28. De Backer J, Bolmsjö G. Deflection Model for Robotic Friction Stir Welding. Ind Robot. 2014;41:365-372.

29. Bres A, Monsarrat B, Dubourg L, et al. Simulation of Friction Stir Welding Using Industrial Robots. Ind Robot. 2010;37:36-50.

30. Mendes N, Neto P, Loureiro A, et al. Machines and Control Systems for Friction Stir Welding: A Review. Mater Des. 2016;90:256-265.

31. Bitondo C, Prisco U, Squillace A, et al. Friction Stir Welding of AA2198-T3 Butt Joints for Aeronautical Applications. Int J Mater Form. 2010;3:1079-1082.

32. Gesella G, Czechowski M. The Application of Friction Stir Welding (FSW) of Aluminium Alloys in Shipbuilding and Railway Industry. J KONES. 2017;24.

33. Ionescu TB, Schlund S. Programming Cobots by Voice: A Human-Centered, Web-Based Approach. Procedia CIRP. 2021;97:123-129.

34. Bi ZM, Luo M, Miao Z, et al. Safety Assurance Mechanisms of Collaborative Robotic Systems in Manufacturing. Robot Comput Integr Manuf. 2021;68:102092.

35. Malik AA, Brem A. Digital Twins for Collaborative Robots: A Case Study in Human-Robot Interaction. Robot Comput Integr Manuf. 2021;68:102092.

36. De Winter J, De Beir A, El Makrini I, et al. Accelerating interactive reinforcement learning by human advice for an assembly task by a cobot. Robotics. 2019;8:104.

37. Villani V, Pini F, Leali F, et al. Survey on Human–Robot Collaboration in Industrial Settings: Safety, Intuitive Interfaces and Applications. Mechatronics. 2018;55:248-266.

38. Tsarouchi P, Matthaiakis AS, Makris S, et al. On a Human-Robot Collaboration in an Assembly Cell. Int J Comput Integr Manuf. 2017;30:580-589.

39. Geravand M, Flacco F, De Luca A. Human-Robot Physical Interaction and Collaboration Using an Industrial Robot with a Closed Control Architecture. 2013 IEEE International Conference on Robotics and Automation. 2013:4000-4007.

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