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Ground and Air Robotic Manipulation Systems in Agriculture

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Preface

Agriculture robotics is an interdisciplinary scientific field that requires the involvement of a wide range of professionals engaged in artificial intelligence, robotics and agriculture. When digitalizing and robotizing agriculture in the open field crop production, it is necessary to account for the territorial distribution, structural and parametric variability of land plots that require the use of group usage of heterogeneous robotic systems, and support of their information, physical and energy interaction should be accounted for. High variability of the physical and geometric properties of agricultural products significantly complicates the process of the configuration design and selection for a robotic agricultural gripper to ensure reliable collection and movement of vegetables and fruits without damage.

The book offers an introduction to intelligent control systems of heterogeneous agricultural robots. The book has resulted from activities of Laboratory of Autonomous Robotic Systems of St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences (SPIIRAS) in the framework of agriculture robotics projects during last 5 year. In July 2020, six research institutions, including those of an agricultural profile, were included in SPIIRAS, and it was transformed into St. Petersburg Federal Research Center of the Russian Academy of Sciences (SPC RAS). Now agriculture robotics is one of the key research directions of SPC RAS.

The book uncovers fundamental principles of heterogeneous robot interaction and recent developments in agriculture robot design. The purpose of the book is to present solutions to the problems of the joint application of heterogeneous ground and air robotic means when performing agricultural technological tasks that require physical interaction with agricultural products and the environment. The book considers the model-algorithmic and software-hardware control of the power supply system for unmanned aerial vehicles, a manipulator and a robotic gripper.

The proposed solutions for the exchange of energy and physical resources of unmanned aerial vehicles on ground service platforms, automation of the process of collecting agricultural products and ensuring the stability of the air manipulation system during physical interaction with a ground object are important for the robotization of the transport and agricultural industry.

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About This Book

The book is aimed at solving the problems of the joint application of heterogeneous ground and air robotic means while performing the agricultural technological tasks that require physical interaction with agricultural products and the environment. The book considers the model-algorithmic and software-hardware control of the power supply system for unmanned aerial vehicles, a manipulator and a robotic gripper.

The tasks' solutions for the exchange of energy and physical resources of unmanned aerial vehicles on ground service platforms, automation of the process of collecting agricultural products and ensuring the stability of the air manipulation system at physical interaction with a ground object that are important for the transport and agricultural industry robotization are proposed.

The book addresses the researchers investigating interdisciplinary issues of agricultural production robotization, problems of information, physical and energy interaction of ground and air robotic systems; it is recommended to postgraduates and students studying "Mechatronics and robotics", "Management in technical systems" and "Technologies, mechanization and power equipment in agriculture, forestry and fisheries".

Important Advantages:

- fundamental principles of heterogeneous robot interaction and their use in agriculture are offered;
- interdisciplinary knowledge and experience acquired at scientific collaboration in robotics and agriculture domains are integrated;
- examples of ground and air robots performing agro-technological operations are considered;
- recommendations concerning the design of agriculture robots' hardware and software are provided.

Introduction

Part I of the book considers the issues of service and control automation of the interaction between heterogeneous agricultural robotic complexes. Robotic means with different levels of functioning autonomy are increasingly used in the agricultural sector, including grain sowing, fertilizing, harvesting and pesticides spraying. The joint use of heterogeneous ground and air vehicles extends the functional and sensoric capabilities of robotic processing of agricultural land. In certain cases, for instance, at servicing power supply systems and transporting air vehicles, arises a problem of physical interaction between the autonomously functioning unmanned aerial vehicle (UAV) and ground service robotic platform (GSRP). This problem-solving complexity is associated with the tasks of landing, fixation and mechanized processing of batteries and agricultural resources placed on the aerial vehicle on the service platform, as well as with the problem of control of the UAV group order of service.

In the above regard, the study of models and algorithms for the interaction between heterogeneous agricultural robotic complexes is a topical research area focused on solving the problem of increasing the UAVs' operating time at long-term autonomous works in agricultural fields that ultimately will contribute to reducing the time and cost of agricultural object processing due to automation and robotic complex application.

A wide range of research and practical works of domestic and foreign scientists (Chernousko F. L., Kalyaev I. A., Ermolov I. L., Vizilter Yu. V., Pshikhopov V. Kh., Meshcheryakov R. V., Kemper P. F., Suzuki K. A. O, Morrison J. R., Kim J. W., Jung Y. D., Lee D. S., Shim D. H., Daly J. M., Ma Y., Waslander S. L. and others) deals with the problems of joint work of heterogeneous robotic means. Continuous improvement of embedded computing and sensor module hardware allows for developing more compact and energy-efficient solutions for a physical connection and exchange of energy resources between autonomous robotic complexes operating in different environments.

In Part I, solutions are proposed aiming at increasing the UAVs' operating time in long-term autonomous modes, as well as at reducing the time and cost of agricultural object processing due to developing models and algorithms for control of the interaction between heterogeneous agricultural robotic complexes, particularly described as follows:

1. A conceptual and structurally functional model of interaction between heterogeneous agricultural robotic complexes, distinguished by the use of closed multichannel multiphase parallel queuing systems with heterogeneous nodes for dispatching and controlling the exchange of energy and physical resources of UAVs on GRSP.
2. A logical-algorithmic model of the interaction of UAVs and GRSP, distinguished by the assessment of internal energy, physical resources, the remaining workload for groups of heterogeneous robots and providing a reduction in time and energy resources of UAVs for movement from the field, as well as takeoff and landing operations.
3. A method for estimating the required composition and amount of equipment for agricultural land processing, distinguished by a multi-criteria assessment using a linear combination of three main criteria of the total processing time, consumed energy, cost of the equipment involved and providing numerical modeling and optimization of the volume of involved heterogeneous robotic systems.
4. Recommendation software system AgrobotModeling, distinguished by the use of numerical and simulation modeling of UAVs and service platform amounts and providing visualization of the functioning of the selected values of input parameters, as well as the choice of the optimal composition and amount of heterogeneous robots.

Part I of the book includes Chaps. 1–4.

Chapter 1 describes the problem of increasing the operating time of unmanned aerial vehicles operating in autonomous agricultural missions. The approaches to charging or replacing onboard batteries on accompanying robotic platforms are analyzed. The existing prototypes of robotic service platforms are distinguished by the complexity of the internal mechanisms, the speed of service, the algorithms for the platform and the aircraft to work together during landing and battery maintenance. Based on the analysis results, a classification of existing service systems installed on robotic platforms for servicing the batteries and built-in UAV containers has been compiled.

Chapter 2 presents the formal statement of the task of interactions between heterogeneous agricultural robots. The developed model-algorithmic support for controlling the interaction between heterogeneous robots' group at the UAV servicing in agricultural tasks is described.

Chapter 3 describes the developed method and system to estimate and support the decision-making on the composition and number of heterogeneous agricultural complexes required to process the given land area, weather conditions and other aspects affecting the work cost and speed. First, a method for multi-criteria assessment of the amount and composition of heterogeneous equipment for agricultural land processing is described, then a graph model for calculating the efficiency of servicing UAV batteries is considered and a recommendation software system AgrobotModeling is presented.

Chapter 4 presents the results of numerical and simulation modeling of the amount of robotic technology for processing agricultural land. The experiments were carried out in the developed program AgrobotModeling, which provides the calculation of the number of unmanned aerial vehicles and ground service mobile platforms involved in the processing of agricultural land of a given area. The program also simulates the functioning of a selected number of robotic equipment, as well as calculates a multi-criteria assessment based on a linear combination of three main criteria: total processing time, total consumed energy and full cost of the equipment involved.

Part II describes the task of multi-criteria synthesis of a robotic gripper configuration for agricultural products' manipulations. Conventional collection and primary processing of agricultural products are the most resource-intensive tasks that require a transition from tedious manual operations to the technological processes' automation and robotization of manipulations with physical objects. At a robotic gripper design, it is necessary to account for a variety of manipulated objects, the complexity of their identification and pointing the manipulator in a complex natural environment with obstacles. The task of synthesizing a robotic gripper mechanism is associated with meeting a number of conflicting requirements to reliability, softness, accuracy, speed and energy efficiency that form a complex space for solutions' search.

So, the study of models and algorithms for optimizing the configuration and control of a robotic gripper performing physical manipulations with agricultural products is an actual scientific direction focused on solving the problem of automation and robotization of technological processes for agricultural product processing.

A wide range of scientific and practical studies made by domestic and foreign scientists considers solving the problems of robotic manipulators' design and control (Zaborovsky V. S., Lokhin V. M., Makarov I. M., Manko S. V., Pavlovsky V. E., Poduraev Yu. V., Yushchenko A. S., Yatsun S. F., Liu J., Van Henten E. J., Feng Q., Bac C. W., Brown G. K., Lehnert C., Han K. S., Bontsema J., Hayashi S., De-An Z. and others). Continuous improvement of control systems and kinematic schemes has ensured a development of serial industrial manipulation robots.

Currently, interdisciplinary studies of robotic complex control are becoming relevant, including those of agricultural grippers, subjected to increased requirements for the accuracy of manipulations as caused by high variability of agricultural products' properties.

In Part II, solutions are proposed aimed at automating the process of collecting agricultural products due to the development of models, algorithms and multi-criteria synthesis for the configuration of robotic gripper and control of its software and hardware components at physical manipulations with agricultural products objects, particularly described as follows:

1. Conceptual and algorithmic models for selecting the parameters of a robotic manipulator and a control system for gripping agricultural products, distinguished by an automated multi-stage analysis of the geometric, mechanical and physical properties of the manipulated object, environmental parameters and potential risks of causing internal and external mechanical damage to agricultural products and ensuring the robotic gripper configuring.

2. Algorithms for multi-criteria synthesis of a robotic gripper configuration, distinguished by a combined application of a posteriori optimization methods and determining the configuration parameter values in the kinematic scheme required at the design and control of the manipulator's end-effector mechanism.
3. Agro-gripper configuration and the algorithm to control operations' cycle of its software and hardware modules for fruits' removing, distinguished by a description of the main stages of physical manipulations of forming the high-level control commands and their execution in low-level software modules implementing interfaces to the hardware means involved in the configuration of a four-fingered robotic gripper with a vacuum bellows.
4. AgroGripModeling software system for modeling the configuration of a robotic gripper, distinguished by the use of three multi-criteria synthesis algorithms, an ability to customize the existing kinematic schemes and parameters proposed in the original classification of agricultural grippers and agro-technological tasks.

Part II of the book includes Chaps. 5–8. Chapter 5 provides an overview of control tasks in regard to technological and robotic operations in agricultural production. The relevance of studying the problems of robotization in agriculture is justified by the good prospects for improving the quality of fresh vegetables and fruits, as well as reducing the cost of production, the necessary labor force and other resources through the development and implementation of agricultural robots. A classification has been compiled for agricultural grippers installed on robotic agricultural equipment and used, e.g., for weed control and harvesting. Also mentioned are the tasks of weeds' directional spraying and/or various plant pruning, with manipulators involvement, however, no targets are reached yet. Some examples of existing research agricultural robots equipped by combined grippers matching the proposed classification and related to various types are given as follows: vacuum gripper with a video camera for grabbing tomatoes; a six-fingered pneumatic gripper with a video camera; a two-fingered gripper with pressure and collision sensors for picking apples; a three-fingered gripper with a video camera for citrus fruits; eggplant grippers and others. The relevance of the joint interaction between a group of heterogeneous ground and air robots at performing agricultural tasks in an autonomous mode is also noted.

Chapter 6 describes the conceptual and algorithmic models for selecting the parameters of a robotic manipulator and a control system for agricultural product gripping. The formal statement of the problem of multi-criteria synthesis of robotic gripping with the definition of target functions and imposed constraints is presented. To evaluate the performance of multi-criteria synthesis algorithms, it is proposed to use indicators responsible for the calculations' quality and speed.

In Chap. 7, a posteriori methods for solving multi-criteria synthesis problems are analyzed and modified. Here is described an example of their use at modeling and selecting values for parameters in the kinematic model of a four-fingered robotic gripper for picking tomatoes. Comparison of simulation results using NSGA-II, MOGWO and MOPSO methods is made. Versions of selecting the objective function, weight coefficients and their influence upon the set of optimal grip sizes are discussed.

Chapter 8 describes the structure of the developed software system AgroGrip-Modeling, providing the modeling and multi-criteria optimization of the robotic gripper configuration. The configuration of the developed robotic gripper for picking tomatoes is described that comprises a four-fingered mechatronic system, a vacuum suction nozzle and distinguishes from existing analogues by using a linear drive to move the vacuum nozzle simultaneously with the four-fingered mechanism movements. The results of modeling and optimizing the configuration of a robotic gripper implementing a posteriori algorithms MOGWO, NSGA-II and MOPSO are presented: a generalized algorithm to control the cycle of software and hardware module operation for robotic gripping at a fetus removing; the results of testing a robotic gripper with vacuum bellows for picking tomatoes are discussed.

Part III considers the motion control problem for an onboard manipulator in maintaining stability of a multi-rotor UAV in hovering mode. UAV equipment with means of physical interaction with ground objects is a new scientific trend in the robotics field. Adding an onboard manipulation system to UAV significantly complicates the operation's algorithm design and leads to an increase in overall dimensions and energy consumption. Physical interaction of the manipulator with objects complicates the process of the UAV stabilizing, which, in turn, leads to difficulties in the UAV positioning and reduces the accuracy of the end mechanism targeting, like the gripper. Besides, the physical interaction of the manipulator with ground objects requires the increased energy resources of UAV.

The development and application of unmanned aerial systems in agricultural production is considered one of the most profitable markets for robotics. Along with the increase of the UAVs' energy efficiency, there appeared a possibility to move from monitoring tasks to more complex ones, requiring physical contact with surrounding objects, manipulating agricultural products and others. Analysis of advanced research in the air robotic manipulation systems confirms the topicality of this study, as focused on solving the movement control problems for the UAV manipulator and its stabilization, specifically used in agricultural technological processes. Scientific and practical studies run by domestic and foreign scientists dwelt upon solving the problems of robotic manipulator control, UAVs and their interaction with ground objects through built-in manipulators (Bobtsov A. A., Voronova E. M., Koshkin R. P., Pavlovsky V. E., Poduraev Yu. V., Filimonov N. B., Yushchenko A. S., Banaszkiewicz M., Heredia G., Kun Xu, Suarez A., Xilun Ding, Yushu Yu, Zihao Wang and others). The studies done were aimed at upgrading the manipulator structure, increasing the stability of the air manipulation system, reducing the mass of the onboard load, minimizing the size of the UAV and increasing the permissible weight and dimensions of the payload.

In Part III, solutions are proposed aimed at ensuring the stability of the air robotic manipulation system at gripping ground objects based on the development of models, algorithms for the manilulator's movement control for an unmained aerial vehicle (UAVM) and its stabilization, particularly described as follows:

1. Conceptual and set-theoretical models of an air robotic manipulation system, distinguished in the description of interrelated entities: UAV, a manipulator, a ground object and environmental factors that provide the problem formulation for developing a model-algorithmic support to control the UAVM movement during physical interactions with a ground object in an environment with various disturbances and obstacles affecting the geometric patency.
2. Algorithm to determine the UAVM acceptable configuration, distinguished by analyzing the typical trajectories of the end-effector mechanism and calculating the range sets for angles between manipulator links, ensuring their movement along the specified trajectories while maintaining the center of manipulator mass on a vertical axis of the air manipulation system.
3. An algorithm for calculating the key points' coordinates for all manipulator links, depending on their joints' angles, based on solving problems of forward and inverse kinematics, distinguished by limiting the displacement of the manipulator mass center, its links and the end-effector mechanism along horizontal and vertical axes, and when the end mechanism moves along the calculated trajectory, it provides the minimum horizontal displacement of the manipulator mass center.
4. UAVM movement control and stabilization system, characterized by the use of a fuzzy PID controller in combination with input calculated data based on polynomial trajectory equations, which ensures the acceptable positioning accuracy of the end mechanism on a given trajectory.
5. UAVManipulatorModeling software system, distinguished by the use of modules calculating polynomial equations of manipulator link trajectories, parameters of fuzzy PID controller, ensuring the modeling and visualization for the influence of disturbing influences on the manipulator vibration occurrence and the ability of the air robotic manipulation system to maintain a stable state by minimizing the horizontal displacement of the manipulator mass center.

Part III of the book includes Chaps. 9–12. Chapter 9 provides an analytical review of existing approaches to solving the control problems for air robotic manipulation systems and the physical interaction of unmanned aerial vehicles (UAV) with ground objects, in particular, while solving problems of agricultural production. The relevance of robotic system introduction to the agricultural production is stipulated by socio-economic reasons and the reduction in the World's freshwater resources. Among UAVs now actively used for land monitoring, land yields' cartogram compiling and fertilization zone planning, multi-copters stand out and their obvious advantage is a vertical takeoff and high sensors' resolution. Multicopters can be equipped with onboard manipulators and sensor means, like video cameras, thermal imager, thermometer, gas sensors, radars, wind speed sensors, pressure sensors, infrared and other sensors. Current studies of UAVs carrying manipulator aboard are professionally discussed and cover the problems of flight control, avoidance of contact with the ground, interaction with the surrounding space, as well as physical interaction with ground objects. Adding the onboard manipulation system to UAV significantly complicates the algorithms of operation, design and leads to the increase in overall dimensions. The physical interaction between the manipulator and objects complicates the process of the UAV stabilizing, what in turn leads to difficulties in the UAV positioning and reduces the accuracy of the gripping pointing. Besides, the physical interaction between the manipulator and objects requires the UAV increased energy resources. The chapter presents an original classification of the air robotic manipulation systems' components, describing various options for onboard facilities necessary for implementing a functional purpose of the UAV with a manipulator.

Chapter 10 describes the conceptual model and general structure of the air robotic manipulation system, new tasks for manipulators' control concerning their base instability and interaction with ground objects. An analysis of the destabilizing factors' impact on the deviation of the end working mechanism movement relative to a specified trajectory is performed. The main task of this study is formulated, as related to the design of a control system for a manipulator installed on UAV and maintaining the center of mass on the vertical axis during movement while interacting with ground objects. Then a number of developed algorithms are described that implement the set task of motion control and stabilization of the air robotic manipulation system.

Chapter 11 proposes a solution to the problem of synthesizing the kinematic and dynamic models of the UAV manipulator, describes the UAVManipulatorModeling software system structure, which provides modeling of the UAV manipulator control and motion as well as its stabilization under the influence of disturbances. The output data are the motion graphs of the manipulator mass center, graphs of the movement trajectory of each manipulator link, graphs of the link angular velocity and angular acceleration. These graphs allow for estimating the manipulator stability when working under the disturbance and without it. In design of a motion control system for the UAV manipulator, it is necessary to calculate the dynamics of the manipulator, determine the motion equations for each manipulator link and calculate the parameters of the manipulator regulator.

Chapter 12 presents the results of the stability preservation modeling for an unmanned aerial vehicle in the hover mode when the manipulator is moving. Modeling was exercised in the absence of external disturbances and their impacts. The experiments were made within the developed program UAVmanipulatorModeling, supporting the calculation and visualization of the trajectories of the manipulator mass center and its end working mechanism. In the study of the horizontal shift of the manipulator mass center, its maximum value was also analyzed at the end of the manipulator movement influenced by disturbing factors that cause instability of the entire air robotic manipulation system.

The described models, algorithms and software are focused on the development of robotic manipulation systems to be implemented in agricultural production and at solving logistic problems of the transportation of the ground objects to difficult accessible localities.

Contents

About the Authors

Prof. Dr. Eng. Andrey Ronzhin born in 1976, is the Director of St. Petersburg Federal Research Center of the Russian Academy of Sciences (SPC RAS)—a legal and consolidated (by joining five more research institutions) successor of St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences (SPIIRAS) since 2020; he held positions of the Director of SPIIRAS (2018–2020), Deputy Director for Research of SPIIRAS (2013–2018). He headed the SPIIRAS Laboratories of Autonomous Robotics Systems (2015–2018), of Speech and Multimodal Interfaces (2008–2015) and of Speech Informatics Laboratory (2003–2007). In 2016, he was awarded the honorary academic title Professor of the Russian Academy of Sciences; he is the winner of the St. Petersburg Government Prize for outstanding results in science and technology for 2017, named after A.S. Popov, and winner of the St. Petersburg Government Award for scientific and pedagogical activity for 2016.

He was awarded his MS in Engineering (M. Sc. Eng.), Ph.D. (Cand. Sc. Eng.), Associate Prof., Dr. Sc. Eng., Full Prof. in 1999, 2003, 2008, 2010, 2013, respectively. He is the founder of the scientific school for studying the multimodal interfaces in the ambient intellectual environment.

The research interests of Prof. A. L. Ronzhin cover modeling of natural communication and development of interactive multimodal information-control and robotic systems; human-machine interaction and robotics. Under the leadership of A. L. Ronzhin, a number of unique technical solutions were made that implemented multimodal interfaces of the surrounding intelligent space, automation of maintenance and control of the interaction of heterogeneous robotic systems. Recently, Prof. A. L. Ronzhin has been comprehensively developing new basic and applied approaches to the introduction of agricultural robotics; his scientific contribution to this field is confirmed by numerous publications, implementations, joint research projects and is recognized internationally in Russia.

Starting from 2000 to the present, Prof. Ronzhin and research team under his leadership work on a number of domestic and more than 10 international projects have been funded and subsidized by the Russian Academy of Sciences, the Russian Foundation for Basic Research, the Russian Science Foundation, the Ministry of Science and Higher Education of the Russian Federation, internationally oriented programs ERA.Net RUS Plus; research projects funded by international organizations include EC IST, EC INTAS, EC FP6, EOARD, and others.

Professor Ronzhin is actively teaching original academic courses for the university undergraduate students and postgraduates in robotics, mechatronics, control of robots and robotic systems, developing intelligent robotic systems, agricultural robots. He is regularly invited to deliver his lectures by the universities abroad. He supervised 8 postgraduates; all the supervised applicants successfully defended their Ph.D. theses. Since 2016, he is Head of Electromechanics and Robotics Department at SUAI. Professor Ronzhin is a chairman of SPC RAS Scientific Council. He is Deputy Chairman of the Doctoral Council D 002.199.01; member of the doctoral council D 999.121.03; member of the Federal Educational and Methodological Association in the field of higher education in the enlarged group of specialties and areas of training 13.00.00 "Electricity and heat power engineering".

He has repeatedly served as the chairman, co-chairman and member of the IPCs at prestigious domestic and international conferences, such as: International Conference on Interactive Collaborative Robotics (ICR); International Conference on Engineering and Applied Linguistics "Piotrovskie Readings"; International Conference on Electromechanics and Robotics "Zavalishin's Readings" (ER(ZR)); International Conference on Digitalization of Agriculture and Organic Production (ADOP). He is Deputy Editor-in-Chief of the Journal *Informatics and Automation*; Associate Editor of the *Int. Journal of Intelligent Unmanned Systems*; *reviewer of Robotics and Autonomous Systems*; a member of editorial boards of scientific journals: *Speech Technologies*; *Analysis and data processing systems*; *System Engineering and Information Technologies*. He is a member of International Academy of Navigation and Traffic Control; the RAS Scientific Council on Robotics and Mechatronics; Committee of the International Association for Speech Communication ISCA; Committee for Eastern Europe of the *International Association for Speech Communication*; Council of Directors of Research and Educational Organizations at the Department of NIT of RAS; Scientific Council for Informatization of St. Petersburg under the Government of St. Petersburg; the supervisory board of the world-class scientific and educational center "Artificial Intelligence in Industry"; expert of the Russian Science Foundation, of the Russian Foundation for Basic Research, of the Russian Academy of Sciences, of the Federal State Scientific Institution NII RINKTSE; Skolkovo Foundation, Russian Venture Company JSC, Science Fund of the Republic of Serbia.

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Dr. Tien Ngo born in 1987, is an Assistant Lecturer of the Aerospace Engineering Department at Le Quy Don Technical University since 2020 and part-time researcher at SPC RAS (2016–2020).

He received his Ph.D. from the joint Dissertation Council incorporating the Bonch-Bruevich St. Petersburg State University of Telecommunications (SUT), the St.

Petersburg State University of Aerospace Instrumentation (SUAI) and the Baltic State Technical University "Voenmeh" of D.F. Ustinov (BGTU); he completed the postgraduate study at the SUAI Department of Electromechanics and Robotics; he received his B.Sc. in aviation engines from Moscow Aviation Institute (National Research University) (MAI) in 2020, 2019 and 2012, respectively.

Dr. Tien Ngo's research interests are agricultural robotics, including models and algorithms for service automation and control of interactions between heterogeneous agricultural robotic complexes; information, physical and energy interaction of ground and air robotic systems.

Dr. Ngo is the author of over 18 refereed journal papers.

Dr. Quyen Vu born in 1987, is an Assistant Lecturer of the Aerospace Engineering Department at Le Quy Don Technical University since 2021 and part-time researcher at SPC RAS (2017–2021).

He received his Ph.D. from the joint Dissertation Council incorporating the Bonch-Bruevich St. Petersburg State University of Telecommunications (SUT), the St. Petersburg State University of Aerospace Instrumentation (SUAI) and the Baltic State Technical University "Voenmeh" of D.F. Ustinov (BGTU); he completed his postgraduate study at the SUAI Department of Electromechanics and Robotics; he received his diploma of specialist in servo drive systems for aerospace vehicles from Moscow Aviation Institute (National Research University) (MAI) in 2021, 2020 and 2011, respectively.

Dr. Quyen Vu's research interests concern, along with the system analysis and information processing, agricultural robotics, including developing methods and models for multi-criteria synthesis of robotic means, like grippers and their configurations for manipulation with agricultural products.

Dr. Vu is the author of over 20 refereed journal papers.

Dr. Vinh Nguyen born in 1988, is a part-time researcher at SPC RAS (2017–2021).

He received his Ph.D. from the joint Dissertation Council incorporating the Bonch-Bruevich St. Petersburg State University of Telecommunications (SUT), the St. Petersburg State University of Aerospace Instrumentation (SUAI) and the Baltic State Technical University "Voenmeh" of D.F. Ustinov (BGTU); he completed his postgraduate study at the SUAI Department of Electromechanics and Robotics; he received his B.Sc. in machine engineering from Le Quy Don Technical University, Hanoi, Vietnam, in 2021, 2020 and 2012, respectively.

Dr. Vinh Nguyen's research interests lie in the field of agricultural robotics and cover design and control of manipulators and robotic grippers placed onboard the unmanned aerial vehicles; he also specializes in the issues of developing applications for manipulators' motion control as aimed at maintaining the developed means' stability in different modes.

Dr. Nguyen is the author of over 21 refereed journal papers.

Part I
Automation of Service and Interaction Control of Heterogeneous Agricultural Robots

Chapter 1
Analysis of Existing Approaches to the Service Automation and to Interaction Control of Heterogeneous Agricultural Robots

Abstract The chapter describes model-algorithmic support of the interaction of UAV and ground-based robotic platforms that carry out the functions of their transportation and service. The problem of increasing the operating time of unmanned aerial vehicles (UAV) in autonomous agricultural missions is discussed. The approaches to charge or replace onboard batteries on an accompanying robotic platform are analyzed. The existing prototypes of service robotic platforms are distinguished by the complexity of the internal mechanisms, the speed of service, the algorithms for the platform and the aircraft to work together during landing and battery maintenance. The classification of existing service systems installed on robotic platforms for servicing batteries and built-in UAV containers has been compiled based on the results of the analysis.

1.1 Analysis of Existing Ground-Based Robotic Service Platforms

An analytical review prepared on the basis of a study of recent publications available in the citation systems of the RIC, Scopus, as well as in the Elsevier, Springer libraries, showed an active study of the problems of robotization of the agro-industrial sector [1–8]. In particular, the problems of precision farming are studied [2, 9–17], robotization in livestock farming [18, 19], application of artificial intelligence systems [20] and other aspects of the use of heterogeneous robotic tools in agriculture [21–30].

In recent years, unmanned aerial vehicles and, in particular, multi-copters (MCs) have been the subject of research by many scientific communities, military and civilian companies. Due to their versatility and the possibility of programming algorithms of their functioning, a wide range of tasks can be accomplished using multicopters, for example, searching for objects, inspecting buildings, observing, etc. One of the main unsolved problems is the need to increase the duration of autonomous work. The average flight time is usually limited to 10–25 min for lightweight multicopters using Li-Po batteries. It is possible to increase the operating time of the

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multi-copter by searching for an improved power source or developing a system of quick battery charging. For the latter option, two types of systems have been proposed: active and passive. Active systems provide a short lead time for the multi-copter, but require sophisticated electromechanical mechanisms to replace an empty battery with a new one. Passive systems are somewhat simpler, but it takes about 10 min to 1 h to charge the MC battery, which increases the delay in completing the MC's main mission. To service UAV batteries options for using service robotic platforms, upon landing on which the UAV charges or replaces its battery to continue the implementation of an autonomous flight mission are now being investigated [31].

A multifunctional mechanism for connecting a MC with a ground-based robotic platform, which carries out the functions of their transportation and maintenance, is one of the main elements [32]. At the moment, three main tasks have been formed, which must be technically implemented on a mobile platform according to its design features, including:

1. charging the MC with the possible implementation of three options for transfer of energy using an energy supply system on the platform (contact connection of the MC battery with the platform power system; replacement of the MC battery; wireless charging of the MC battery);
2. contact interaction of the platform with a set of MC, including the MC and the platform docking mechanism, involving the safe movement of the MC on board the platform, landing and the take-off of the MC;
3. communication of the mobile platform with the MC and the base station. Next, we will analyze the existing solutions for the above three tasks.

Autonomous UAV landing in modern research is considered not only on a fixed site, but also on a mobile platform moving in different environments. The UAV landing on the service charging station is carried out using various navigation systems and analysis of the surrounding area. The paper [33] proposes a vision system capable of detecting UAV and accompanying it before landing on the platform. Recognition of UAV templates will allow assessing its position and orientation when approaching the landing site. The proposed system operates in real time on onboard computing resources indoors and outdoors without the support of global navigation systems.

A new decentralized method of controlling the joint functioning of a UAV and a mobile platform is considered in paper [34]. The presented experimental results for the small quadcopter Aeryon Scout and the Clearpath Robotics A200 Husky mobile platform confirm the possibility of landing both indoors with high-quality navigational data and outdoors in windy conditions.

The work [35] proposes a system for tracking a mobile platform and monitoring the landing of a UAV on it. The system uses a detection and location algorithm for landing sites based on technical vision and an omnidirectional camera with high image quality. Analysis of the video stream makes it possible to assess the position and speed of the mobile platform relative to the UAV. The landing system was tested on a quadcopter that successfully landed on a mobile platform during outdoor flight tests.

In [36], an algorithm for autonomous UAV landing on the deck of a ship is considered. A movable landing pad with six degrees of freedom used in the experiments to simulate the dynamics of various ships and sea states. The developed technical vision system uses the Kalman filter to ensure the reliability of estimates, to determine the position of the UAV relative to the platform, with special graphic marks.

Analysis of energy consumption of the built-in mobile platform modules equipped with a two-axial turning area for UAV landing is considered in the paper [37]. To achieve a longer service platform operating time, it is recommended using more efficient sensors rather than increasing the size of the built-in rechargeable batteries. In addition, solar panels are installed on the platform, prolonging its operation and maintenance of the UAV.

To increase the autonomy of an unmanned aerial vehicle, it is required, among other things, to recharge its energy source and replenish other consumables based on automated recharge systems. In the paper [38], two types of automatic systems for recharging the MC on a ground-based platform were developed with battery charging and replacement with a new one. Systems with a replaceable battery can significantly reduce the time for preparing an MC for a new flight and increase the total number of MCs co-located in an autonomous mission. The recharging system has a lower cost compared to the battery replacement system by minimizing mechanical components of the structure.

In the work [39], the basic approaches to increasing the flight time of a UAV by reducing energy consumption are considered, in particular:

1. the use of new lightweight materials;
2. reducing the energy consumption of on-board devices;
3. improving the aerodynamic characteristics of the UAV;
4. the use of hybrid constructing schemes of UAV, including the use of aerostatic unloading of aircraft and helicopter-type UAV;
5. dynamic routing of UAV group's flights;
6. as well as a non-trivial solution—that is dropping of discharged power sources and thereby reducing the UAV mass.

In the work [40], it is substantiated that the search for the optimal trajectory of the UAV group, with periodic maintenance of energy supply systems on the accompanying group of ground-based mobile charging stations for some mission, is an NP-complete task, and a number of modifications to linear programming methods and heuristic approaches are proposed to solve it.

In the work [41], UAV are considered to be vehicles, the cost of their mass use is estimated, including service at fixed refueling stations and the sequence of processing of UAV and dynamic delays at the arrival of UAV.

In the paper [42], various approaches to controlling UAV motors are investigated in order to optimize energy consumption. Also, there are three levels of UAV control, at which energy costs can be optimized:

1. higher—the calculation of trajectories of movement, taking into account the overflow of obstacles and minimization of time (or energy consumption);

2. medium—calculation of kinematic and dynamic models of UAV movement along a given trajectory at the required speed;
3. the lowest—the calculation of the parameters of voltage controllers and converters, current sources to maintain the required rotational speed of the UAV rotors. For the lowest level of control, the methods of Lyapunov, linear algebra, and PID controller are compared. At the same time, it is noted that the first methods allow reducing energy consumption, but require a long tuning process, and the PID controller is still the simplest and relatively effective approach.

Work [43] also reviewed approaches to reducing the energy consumption of UAV motor control systems. The analysis of the efficiency of various current sources, as well as the energy consumption of the UAV at various stages of operation: takeoff, climb, flight, lowering, landing. The most energy-consuming stages during the climb and landing (maneuvering while positioning to a given landing site) require special attention and optimization of control algorithms. The advantages and disadvantages of heuristic, intelligent (fuzzy logic, artificial neural networks, etc.) and optimization (dynamic programming, etc.) methods are given.

In the work [44], it is noted that multi-copters are highly maneuverable UAV and are used to fly over complex trajectories in a confined space with a large number, including dynamic obstacles. Maneuverability certainly affects the high energy consumption, as well as the need to reduce the weight of the multi-copter by reducing onboard energy resources. The developed UAV wireless battery charging system features differ from the VICON camera system for accurate positioning and is fully automatic, which significantly reduces the maintenance cost.

In the paper [38], three types of UAV battery charging stations are proposed: Rollin' Mat, Concentric circles, Honeycomb, they differ in cost, capabilities, and functions. Rollin' Mat and Concentric circles power stations are simple in design, easy to install and relatively inexpensive. However, the location and size of the terminals at the station depends on type of the aircraft, which naturally affects the size of the landing area at the station. In particular, if the UAV is rather small, then the landing accuracy provided by navigation systems may be insufficient for docking with charging pads. The Honeycomb power station has many advantages, the system is easily expandable: a large number of UAV can be charged simultaneously by adding additional cells and chargers. Another feature is that the wireless IR emitter/sensor of the communication system can be easily replaced with another wireless system. Honeycomb can be used in almost any situation where recharging is needed. But this solution is more expensive, therefore the Honeycomb platform is recommended in cases where precise landings are required on a small site in difficult weather conditions.

Also in [38], a system for replacing the UAV battery was proposed. The use of the system significantly increases the coefficient of the maximum flight time and reduces the time spent and the number of UAV on the platform. On the other hand, the cost of implementing the system increases, because replacing an empty battery is more difficult than charging a UAV. For the functioning of the UAV battery replacement system, the implementation of the following functions is required: determining the position of the UAV, mechanizing the battery replacement process, charging the battery, operating of the battery store, transporting the batteries inside the station.

Work [37] presents design options for functional components for replacing batteries at a service station. The developed system for replacing UAV batteries is designed to automatically replace discharged UAV batteries with new ones without human intervention. The main tasks of this system are as follows:

1. sending the UAV to the battery replacement station;
2. UAV navigation to the station;
3. fixing the UAV at the station;
4. connection to the UAV: removal and placement of batteries;
5. transportation of batteries;
6. recharging batteries.

As a rule, ground-based service stations are located in the open air, where weather conditions cannot be predicted and the landing of the UAV is accomplished with some error. In the work [45], an approach that allows a UAV to get to the place of battery replacement, even if its landing site is not ideal due to navigation errors, weather conditions, damage to the UAV, and other factors, is considered. The mechanism by which the battery is securely fixed and physically connected to the UAV is also important, because it affects the complexity and time of battery manipulation. In addition, its additional weight will affect the size of the UAV's payload and flight time. In order to create an interface between the UAV and the platform, mechanical and magnetic couplings, which can easily hold and release the battery, while simultaneously providing a terminal connection to the UAV, are considered.

During the operation of the service station in work [45], several modules are used to replace the batteries with high accuracy:

1. battery fixation and orientation module;
2. UAV locking/unlocking module;
3. battery extraction module;
4. battery replacement module. The station can compensate for orientation and positioning errors of the UAV during a landing. The proposed design of the ground-based station can also handle dissimilar UAV not only with different shapes and sizes, but also with different numbers of batteries.

To recharge the batteries, the MC remains on the platform until full charge, so the time that the MC spends on the platform is no less than the time it takes to charge the batteries. In a battery replacement system, this time is less, because only mechanical manipulations are carried out to change the power supply [45].

1.2 Analysis of Requirements and Restrictions of Mobile Battery Maintenance Systems for Unmanned Aerial Vehicles

Automation of the process of recovering the energy resources of the multi-copters on the ground-based robotic platform in the target solution area will allow to increase the duration of the multi-copters' operation and the number of the tasks in the autonomous mission. Increased autonomy for the operation of UAVs and in particular multi-copters in the target area by the automatic charging system is the subject of many scientific studies. Mainly there are two types of station recharging—system of charge battery and systems with battery replacement. Systems with battery replacement can significantly shorten the preparation time of the multi-copters for a new flight and increase the total number of multi-copters that are simultaneously in the autonomous mission. The recharging system has a lower cost compared to the battery replacement system due to the minimization of the mechanical components of the structure.

First, the development of charging robotic ground-based stations is relevant for solving the problems of monitoring remote territories, in which most of the energy resources are used on reaching the specified area. In this case, multi-copters have the opportunity to replenish their energy resources in the territory of operation and work in a continuous mode until the end of the platform resources. Second, the developing charging system solves the problem of automating the battery maintenance process and could be used in fixed locations. In the framework of this study, models and prototypes of the battery charging system are developed, characterized by wireless transmission of energy, mechanization of the manipulation process with the battery on the multi-copter and the service platform.

Now ground-based robotic systems and unmanned aerial vehicles, including multi-copters are actively used in various industries both for solving applied specialized tasks and for the entertainment industry [8–10]. Considering the wide range of operators training and functional capabilities of the multi-copters, it is necessary to identified three most popular applications of multi-copters:

1. researchers;
2. farming;
3. security [46].

Table 1.1 shows the basic requirements for service systems of energy supply systems for the three above categories [38]. Agricultural MCs monitor the movement of cattle, check the integrity of fences, control the quality of soil and crops, and spray agricultural fertilizers. The use of MC for entertainment, educational and research purposes are carried out during pilot training, modeling of single and group behavior, including in difficult weather conditions.

Different customers also have different design constraints (budget, weight, complexity), but it is possible to identify some major common constraints; they are summarized in Table 1.2.