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A Review on Cooperative Robotic Arms with Mobile or Drones Bases

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Abstract: This review paper focuses on cooperative robotic arms with mobile or drone bases performing cooperative tasks. This is because cooperative robots are often used as risk-reduction tools to human life. For example, they are used to explore dangerous places such as minefields and disarm explosives. Drones can be used to perform tasks such as aerial photography, military and defense missions, agricultural surveys, etc. The bases of the cooperative robotic arms can be stationary, mobile (ground), or drones. Cooperative manipulators allow faster performance of assigned tasks because of the available "extra hand". Furthermore, a mobile base increases the reachable ground workspace of cooperative manipulators while a drone base drastically increases this workspace to include the aerial space. The papers in this review are chosen to extensively cover a wide variety of cooperative manipulation tasks and industries that use them. In cooperative manipulation, avoiding self-collision is one of the most important tasks to be performed. In addition, path planning and formation control can be challenging because of the increased number of components to be coordinated.

Keywords: Cooperative arms, mobile manipulator, aerial manipulator, mobile base, drone base, cooperative tasks.

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1 Introduction

Cooperative manipulation has become part of our day-to-day activities, slowly replacing the human workforce in highly repetitive work or in remote areas inaccessible to humans. Mobility of robot bases, including mobile bases or flying bases, has become an integral part of cooperative manipulation because it drastically increases the reachable workspace for manipulation. Robots are often used as risk-reduction tools to human life. For example, they are used to explore dangerous places such as minefields and disarm explosives[1].

Drones can be used to perform tasks such as aerial photography, military and defense missions, agricultural surveys, etc. In the case of drones with arms, very few platforms are available. However, there is a wide promising area of applications for such technology, e.g., seven-degrees-of-freedom (7-DOFs) robot Kellerand Knappich Augsburg (KUKA) arm attached to a unmanned aerial vehicles (UAV) helicopter[2]. This extended the workspace of the robot and they acknowledged that they experienced problems such as increased kinematic errors, which were solved by employing a task space decoupling approach. Kim et al.[3] developed a quadrotor with 2-DOFs robotic arm, in which they claim that they have developed kinematic and dynamic system models to perform tasks such as picking and delivering objects. Hexacopter drones[4] are able to carry cargo and move chairs. These hexacopter drones may be equipped with dual arms[5, 6]. They presented task-space modular dynamics and modular relative Jacobian for dual arms and successfully performed a chain cleaning task. Therefore, this review paper recognizes the need for drones with robotic arms for aerial manipulation, single or cooperative.

This survey reviews topics on robotics arms with mobile or drones bases in cooperative manipulation, starting with robots attached to mobile bases also known as mobile manipulators, dual arms for cooperative manipulation, legged robots or humanoids, types of robots′ controllers for cooperative manipulation, robotic arms attached to drones, results analysis, and lastly the conclusion or future directions. This is to show the diverse robotic controllers for stationary, mobile and aerial robotic manipulators. The survey goes on to show all the limitations and advantages of such robotic controllers as well as possible ways of improving the systems.

This survey is divided into sections, namely: cooperative robotic arms, cooperative mobile bases, cooperative mobile manipulators, controllers for the cooperative mobile robots, drones with robotic arms, results analysis, and lastly, the conclusion on studies carried out. Furthermore, this study shows the importance of the dynamic co-

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operative robotic controllers and will help the robotic community in further development of cooperative robotic controllers, improving existing ones.

2 Cooperative robotic arms

Robotic systems for object manipulation[7, 8] require extensive computation on robot motion planning and force control during object and environment interaction. In cooperative robotic systems, the complexity is even higher since task distribution, planning, coordination and cooperation of each arm are required. The robotics research community developed several multi-robotic systems for cooperative tasks[9–11] to have an integration framework that allows coordination and cooperation in real environments. Rodríguez et al.[12] presented a dual-arm framework for cooperative applications to coordinate and synchronize dual-arm robotic systems and task executions in real environments. The robot operating system (ROS)[13] was used as a communication layer of the dual-arm system.

Sections 2.1 and 2.2 will discuss in detail the examples of dual-arm robots, kinematics analysis, and their design of coordination followed by multiple robotic arms cooperation. The same analysis criteria (design of coordination and kinematic analysis) will be adopted in Sections 3 and 4.

2.1 Cooperative dual-arms

The design and simulation of single-arm manipulators have been around for quite some time. We mention some studies here to give the reader some background of the issues facing single-arm manipulators. Zhang et al.[14] designed and simulated two robotic manipulators, each with two links, driven by direct current (DC) motors and flexible forearms. The study is proved to be effective in tip vibration suppression and reducing the effects of tracking errors. Awelewa et al.[15] presented the design and development of a robotic arm controller in a laboratory environment, and the study successfully implemented algorithms and servomotors to control independent joints. This resulted in a successful operation of the manipulator. The robotic arm contains accelerometers that give feedback to the micro-controllers, and the control algorithm was implemented in Matlab. In [16], a robotic arm successfully performed a pick and place operation using Arduino and accelerometers. The study reduced limitations in manual object control for sorting systems, although rotating angles of servo motors could not exceed 180 degrees. As a result, the study rectified this by preparing a new mathematical model and solved angular rotations. In [17], a disturbance observer-based controller is proposed such that the controller performs relatively well even with different or distinct disturbances. They claimed to have positively verified this control theorem against different disturbances and different robot manipulator setups or configurations. Also, the controller can cope with instantaneous time-varying external disturbance. Song et al.[18] focused on the mathematical model of the whole robotic arm and mentioned challenges on dynamic and static friction forces. The study automatically switched between the models to avoid ambiguous situations and illustrated dynamic simulations of the robotic arms.

Fig. 1 is YuMi (IRB 1 400-0.5) robot, a dual-arm robot with two arms that are capable of adding flexibility to assembly processes and shortening manufacturing cycles[19].

The study developed a dual-arm industrial robot for assembly automation of automotive parts consisting of two industrial 6-DOFs arms and one 2-DOFs torso, which plays a pivotal role in the assembly of automation parts[20]. This bridged single-arm manipulation limitations, especially where operations are done with two hands. Recent developments in sensor technology, motion controllers, and machine learning have made robots more intelligent and robot collaboration more realistic[21]. For cooperative dual arms[22] to perform diverse and complex tasks, the robotic arms have to imitate and learn how humans work[23]. They claimed that the neural network architecture exhibited learning and communication and that robots were able to imitate complex actions like opening a door.

Table 1 summarizes fixed-base dual-arms with different robotic arms' DOFs and their payloads with their manufacturing companies. The dual-arms have proven to be very useful in automated assembly industries because of their high-precision capability, contrary to the human labor force.

2.1.1 Kinematics analysis of dual-arm manipulators

Designing a dual-arm robot for industrial assembly involves analyzing its workspace and performing dynamic motion simulation[27]. By doing so, they claimed to have successfully designed a dual-arm robot with a torso joint. The most important function of the dual-arm manipulator is the cooperation between the arms and the postures needed for cooperation tasks. The arm postures and hand locations are needed for assembly tasks as they are the ones doing cooperation and not the torso of the robot[28]. Park et al.[29] developed a mobile dual-arm manipulator

Fig. 1 An Example of a dual-arm robot, YuMi by ABB reprinted with permission from [19]

Table 1 Examples of dual-arm robots

Robot	Company	DOFs	Payload (kg)
Blue (lightweight)[24]	UC Berkeley	7	2
Baxter (low cost)[25]	USA Rethink Corporation	7	2.25
YuMi (IRB 1 400-0.5)	ABB	7	1
Justin DLR-LWR-III[26]	German Aerospace Center	7	7−15

for the automatic assembly of electrical devices. Furthermore, the researchers managed to improve the robots′ positioning by using force-torque feedback and they want to improve their research by manipulating multiple larger objects. Park et al.[30] designed a dual-arm rescue robot loaded on a mobile robot to perform human rescue activity on the battlefield. In this study, there were limitations on existing dual-arm robots, one of them being that the dual-arm robots are confined to indoor operations. The study faced issues in friction modeling of worn-out parts and external vibration. Dual-arm robots need to be highly precise, and as a result, Freddi et al.[31] developed a fault-tolerant controller for dual-arm manipulation systems based on the relative Jacobian method. The study claimed that its fault-tolerant controller changes the configuration of both manipulators without changing or affecting the desired relative end-effectors distance.

2.1.2 Design of coordination for dual-arm manipulators

Coordination of robot manipulation results in increased manipulation performance and redundancy. However, Erhart et al.[32] showed that cooperative systems incur kinematic errors originating from geometric uncertainties limiting cooperative task performance. An impedance-based control architecture was implemented to fix the kinematic errors. To coordinate dual-arm manipulators, Hebert et al.[33] combined visual and kinesthetic information to estimate both the manipulator and the object states using an unscented Kalman filter (UKF). They successfully performed dual-arm manipulation tasks such as wheel changing. Another approach to coordination for dual-arm manipulators is by using a master/slave technique[34]. They claimed to have successfully demonstrated autonomous control used for coordination and control. Also, to perform coordinated motions, Park and Lee[35] described extended cooperative-task space (ECTS) performance indices that can enable redundancy in the dual-arm system to be effectively utilized for a larger range of workspace. Calibration of a cooperative system is critical to its accuracy, therefore, Bonitz and Hsia[36] recommended calibration tools like theodolites, laser interferometers, coordinate measuring machines, acoustic sensors, optical sensors, and wire potentiometers to help in calibration of the system.

2.2 Three or more robotic arms cooperating

It is necessary to have multiple arms cooperating in some automated manufacturing or assembly entities[37]. And some multiple arms robots are used in high precision tasks[38]. In this study, force/torque sensors were used to measure trajectory errors and transducer signals to measure end-effector deformations. A computer-based simulation was then used to show the effectiveness of this approach. They state that closed kinematic chains help in precise cooperative or simultaneous object manipulation.

Fig. 2 Example of a wheeled robot, Rollin′ Justin, re-printed with permission from [26]

As a result, the control approach of multiple robotic arms will differ from that of single or dual arms. Because in the control of multiple robotic arms, there is a need to coordinate the motion of multiple robotic arms with one another for stable object manipulation.

2.2.1 Kinematic analysis of multi-arm manipulators

A robot multi-arm control system includes robot controllers that use a communication link to transmit synchronization information from the master controller to slave controllers for coordination purposes[39]. They state that this system takes care of communication delays, especially during motion synchronization. Concerning motion coordination of redundant robot systems, Khatib et al.[40] developed an augmented object model and virtual linkage model for fixed-base multi-arm robots. The study claims to have successfully designed two holonomic mobile manipulation platforms. Koga and Latombe[41] claimed to have automatically generated motion paths for several cooperating robot arms to manipulate a movable object avoiding collisions among obstacles. Moreover, Cheung and Chung[42] extended the single-master-single-slave (SMSS) to SMSS telemanipulation using semi-autonomous adaptive control methods to compensate human operator errors by modifying the paths for the leader robotic arm. Section 2.2.2 will describe the design of cooperation for the multi-arm manipulators.

2.2.2 Design of cooperation for multi-arm manipulators

As interests in mobile cooperative multi-arm robots grew, Hichri et al.[43] adopted a co-manipulation method using army ant's strategy to improve stability of payload. Detailed structural and dimensional analysis aided the lifting process of the payload. Different types of controllers for multiple robotic arms may be implemented for cooperative purposes like adaptive bilateral control, multilateral control[44], and impedance control[45]. They will be discussed further in the controller part of this paper.

3 Cooperative mobile bases

Cooperation in mobile bases comes in different forms, which can display swarm behavior. A swarm of mobile bases cooperatively performing a task increases the operational area and tasks attained[46]. Cooperative mobile bases not only enlarge and expand individual robot capabilities but also improve their manipulability[47]. They presented a framework for coordination control of vehicle-arm systems. The framework provided helped demonstrate vehicle-arm coordination and cooperative operations between two platforms. Another form of cooperative mobile bases is shown in Fig. 2. It can be used in numerous tasks such as catching balls, making coffee, and learning to fix satellites.

3.1 Kinematic analysis of mobile bases

There are two types of mobile bases based on their moving platforms: wheeled and tracked mobile bases.

3.1.1 Wheeled mobile base

Wheeled robots are much easier to design, build, and program for movement in flat, not-so-rugged terrain[48]. The motion of the wheeled mobile base is fully dependent on the rolling capabilities of the wheels[49], which can rotate indefinitely, backward, or forward. The combination of wheels and joints in articulated wheeled robots allowed them to adapt their morphology to the terrain, thus increasing their maneuverability[50]. As a result, two-wheeled robots like the innovative two-wheeled mobile robots (2WMRs)[51] attracted many studies. Mu et al.[52] successfully developed a rotate-and-run scheme for cooperative control of a group of 2WMRs to solve the consensus problem for a group of under-actuated 2WMRs. Mas and Kitts[53] presented a cluster control approach to achieve object manipulation using a cooperative mobile multi-robot system. This approach maintained that only a single user using a joystick could control all robots in a formation. In [54], a rigid-formation-motion (RFM) framework is proposed to control multiple non-holonomic robots. It is claimed to have achieved cooperative cooperation manipulation and transportation of rigid objects using two-wheeled robots. Also, Dong and Farrell[55] discussed a dynamic control law for multiple mobile agents. It claimed that the mobile agents tracked moving target objects and various simulations were made to validate the effectiveness the controller. Nagasaka et al.[56] proposed a whole-body force controller for a mobile robot with a manipulator. They claimed that the robot could achieve coordinated diverse motion objectives such as velocity, acceleration, and impedance at any part of the robot. Fig. 3 shows an example of a Robotnik wheeled robot.

Fig. 3 Example of a wheeled robot, called Robotnik, re-printed with permission from [57]

3.1.2 Tracked mobile base

Guarnieri et al.[58] claimed to have modeled and simulated a search and rescue crawler robot. Furthermore, Inoute et al.[59] asserted that optical tactile sensing systems could estimate contact conditions of surface in a non-contact way using phototransistor. Tracked mobile bases have external structures similar to that of a tracked vehicle (excavator), as shown in Fig. 4.

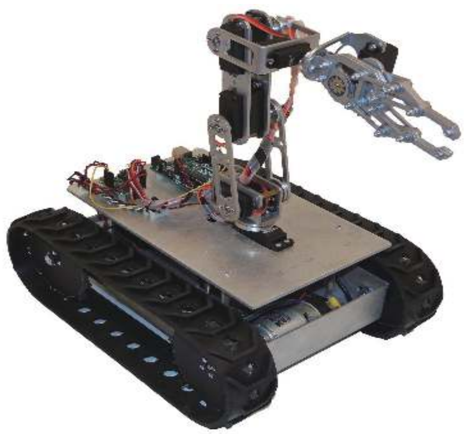

Fig. 4 Example of a tracked robot re-printed with permission from [60]

3.2 Design for cooperation of mobile bases

Cooperative robotic mobile bases can be used in controlling a formation, guarding a perimeter, and surrounding a facility[61]. Cooperative mobile bases may imitate biological groups such as a group of ants[62] and a parade of fish[63]. Van Den Broek et al.[64] proposed a virtual control strategy with mutual coupling in the design for the formation control of unicycle mobile robots. Yi et al.[65] stated that designing an extended Kalman filter (EKF) for mobile robots played a huge role in robot positioning and wheel slip-estimation schemes.

4 Cooperative mobile manipulators

Khatib[66] discussed mobile manipulation and developed robotic capabilities that aid humans in various physical operations. Desai et al.[67] showed that cooperative mobile manipulators could be used to share payloads that cannot be handled by a single robot alone, thereby enhancing their working volume and grasping capability.

4.1 Kinematic analysis of mobile manipulators

Yamamoto and Yun[68] presented a unified approach to the task space analysis of mobile manipulators treating both locomotion and manipulation in the same framework from the viewpoint of the task space. Giftthaler et al.[69] introduced a constrained sequential linear-quadratic optimal control algorithm (constrained SLQ) to address the problem of kinematic trajectory planning for mobile manipulators. Furthermore, Oriolo and Mongillo[70] developed a greedy planner, rapidly exploring random tree (RRT) like planner and variations on RRT-like algorithms to solve motion planning along end-effector paths (MPEP) problems.

4.2 Design of cooperation for mobile manipulators

Sugar and Kumar[71] highlighted that robots can cooperatively transport objects and march in a tightly controlled formation and autonomously navigate to their target. To address the design of autonomous cooperative platforms, Sugar and Kumar[72] developed a real-time control system and a forklift-like arm scheme, which easily allowed the control of Cartesian stiffness or impedance. In [73], a decentralized neural network (NN) control system was developed, which can respond more quickly to known and measurable disturbances. Simetti and Turetta[74] claimed that a dynamic programming (DP) approach could be used to deal with multi-mobile manipulators cooperatively accomplishing the transportation and manipulation of a shared load.

5 Control of cooperative robots

This section briefly reviews cooperative controllers for manipulators, mobile bases, and mobile manipulators, unlike in Sentions 2−4 which only focused on the kinematic analysis of robots and their design for coordination.

5.1 Control of cooperative manipulators

Tinos et al.[75] proposed a hybrid control of motion and squeeze force and claimed that it does not use the robots′ inertia matrices. It developed a squeeze force controller which independently treats the components of squeeze forces. Incremona et al.[76] focused its scope on designing a hybrid sliding mode position and force controllers and claimed it is robust in trajectory tracking even in the presence of external disturbances. A multiple impedance control (MIC) was designed by [77] to designate impedance on all cooperating manipulators and to tune inner forces or torques when manipulating an object. To control the motion and internal forces of the target object as well as the contact forces between the object and environment, Heck et al.[78] proposed a cascade control algorithm. A decentralized adaptive hybrid intelligent control scheme proposed by [79] claimed to have achieved control objectives starting from partial or no prior knowledge of the system′s dynamics. Moreover, Gueaieb et al.[79] used the Lyapunov stability approach. Phukan and Mahanta[80] designed a position synchronization controller based on an integral sliding mode for dual-arm manipulators. The study mentioned that the controller ensures stable object manipulation while following the desired trajectory. It claimed to have tested the controller on a 14 DoF dual-arm robot, and the controller showed efficiency in trajectory tracking and can withstand external disturbances.

In the following subsections, we present additional types of controllers for cooperative manipulators, namely: adaptive Jacobian control, decentralized adaptive control, impedance control, and robust adaptive fuzzy control scheme.

5.1.1 Adaptive Jacobian control

Zhao et al.[81] developed an adaptive Jacobian synchronized tracking control approach and showed that the approach could stabilize position tracking of each manipulator while coordinating its motion with other manipulators. Zhao et al.[81] also mentioned that the bench test of the approach is proved very effective.

5.1.2 Decentralized adaptive control

Itoh et al.[82] proposed a decentralized control of cooperative manipulators based on the virtual force transmission algorithm. It mentioned that all the forces (grasping and accelerating forces) are calculated at the end effectors. Furthermore, Itoh et al.[82] incorporated a space observer to correct the tip motion response errors and implemented the decentralized control method through a series of simulations and experiments.

5.1.3 Impedance control

Caccavale et al.[83] designed an impedance control for cooperative dual arms encompassing a centralized impedance control method. This control strategy is based on a two-loop configuration in which a proportional-integral-derivative (PID) inner motion loop is adopted on each manipulator. The development was tested on a dual-arm with 6-DOF on industrial robots carrying an object.

5.1.4 Robust adaptive fuzzy control scheme

Gueaieb et al.[84] focused on designing an adaptive fuzzy control scheme for cooperative manipulators to tackle simultaneous position and internal force control issues. This approach was made amid unwanted parametric and modeling uncertainties as well as external forces or disturbances. They also claimed to have taken advantage of the Lyapunov stability approach, and the controller was affirmed robust even in the presence of external forces and uncertainties.

Fig. 5 shows an example of cooperative manipulators.

Fig. 5 Deep learning robotics (DLR) cooperative manipulator re-printed with permission from Institute of Robotics and Mechatronics, Germany[85]

5.2 Control of cooperative mobile bases

Cooperative mobile base controllers are discussed in this section, namely, fault-tolerant cooperative controller (FTCC), slide-mode formation control, target tracking control, and visual observation and fuzzy logic control. Fig. 6 shows cooperative KUKA mobile platform 1 500, KUKA omniMove, and KUKA triple lift ensuring high-precision transport equipped with navigating systems for a fully automated operation[86].

5.2.1 Fault-tolerant cooperative controller

An FTCC for autonomous wheeled mobile robots was developed by [87] based on cooperative control. It applied the Hungarian algorithm and a collision avoidance algorithm based on the mechanical impedance principle, which avoided potential collision between healthy robots and faulty ones in a team configuration. This is designed such that if there are some faulty robots, the remaining robot tasks are reassigned to the healthy robots to assure mission completion. Furthermore, it was designed to re-coordinate the motion of each robot in the team.

5.2.2 Slide-mode formation control

Defoort et al.[88] discussed the first and second order sliding mode controllers to stabilize mobile robots. It was

Fig. 6 KUKA omniMove mobile platform re-printed with permission from [86]

based on relative motion states, which eliminate the need for leader robot velocity estimation. Moreover, they stated that formation stabilization is done by a vision system incorporated on follower robots ensuring robot collision avoidance.

5.2.3 Target tracking control

Wang and Gu[89] focused on solving a moving target tracking problem for multiple mobile robots. The problem was subdivided into two: an estimation of target position, and flocking control of a group of robots advancing towards the target object. It used a novel distributed Kalman filter and a distributed flocking algorithm. It validated the development of simulated 2D and 3D robots and affirmed that the suggested algorithms helped track a moving target. Finally, they mentioned that cooperative target-tracking robots outperformed the results produced by individual target tracking robots.

5.2.4 Visual observation and fuzzy logic control

Marapane et al.[90] described visual observation and fuzzy logic control strategies for cooperative robotic team motion controllers. It highlighted that the robots demonstrated a coordinated convoying behavior. Visual observation helped in coordinating the team using visual servoing to track the leader robot. To determine leader headings, it used a minimum noise and correlation energy (MINACE), whereas a real-time fuzzy logic motion controller was used to adjust the leader velocity.

5.3 Control of cooperative mobile manipulators

Safe transportation of objects in an environment with external disturbances or obstacles is a challenging task, and many studies are trying to develop a controller to address the challenge[91]. The following control strategies are discussed in this section: centralized-decentralized architecture, local information-based control law, decentralized control, and adaptive cooperative control.

5.3.1 Centralized-decentralized architecture

A centralized-decentralized architecture[91] addressed the problem of cooperative object transportation by cooperative mobile manipulators. This strategy was designed with two layers. The higher layer was centralized and dealt with collision-free path planning using an optimally connected random tree. At the same time, the lower layer was decentralized and dealt with inter-robot motion coordination and transportation of the target object. It implemented the strategy in Webots™ software for KUKA youBot.

5.3.2 Local information-based control law

A local information-based control law[92] was proposed to solve the problem of multiple mobile manipulator robots rotating a grasped object to a targeted location. It adopted a multi-agent system approach assuming that: The agents can sense relative positions of each other, there is an exchange of information amongst the agents, and there is a communication topology. It noted the issue on the stability of this control law.

5.3.3 Decentralized control

Two novel solutions were considered[93] for a fully and partially decentralized cooperative control of multi-mobile robots with load manipulation. The two controllers discussed were: a fully decentralized controller, which dealt with parameter estimation and twist of the load, and a partially decentralized controller to ensure precise tracking of load and twist. The fully decentralized controller also ensured the stability of the load twists.

5.3.4 Adaptive cooperative control

A multi-layer scheme[94] was presented for adaptive cooperative control of mobile manipulators. The multilayer scheme work had independent modules dealing with cooperation, coordination, and adaptation problems. To prove the robustness and stability of the system, it used Lyapunov theory and maintained that the simulation results were positive.

Fig. 7 shows an example of cooperative mobile manipulators by fetch robots.

6 Drones with robotic arms

As in the previous sections, this section discusses the application and examples of drones with robotic arms and their significance together with their technical specifications. This section will discuss individual control of drones with robotic arms 6.1 and cooperative control of drones with robotic arms 6.2.

Fig. 7 Cooperative fetch mobile manipulators re-printed with permission from fetch robotics[95]

Robotic manipulators attached to mobile bases are often used in areas that need the end-effector to mobilize beyond its reach. As mentioned in [96], assistive robots[97] used a heterogeneous multi-robot system to assemble long components, ship painting, building, and welding[98, 99]. The papers stated the need to stabilize the UAV in flight and introduced an integrated underweight Delta manipulator, aircraft maintenance, etc. Campos et al.[100] added that these areas are challenging for human operators due to the risks associated with them. One of the challenging topics in drone control is precision flight dynamics, and Al-Fetyani et al.[101] claimed to have implemented an adaptive neuro-fuzzy inference system (ANFIS) based control system. The study claims that the system improves attitudes and altitudes performances of drones (quadcopter). The system was tested in a simulated environment and demonstrated the ability to reject external disturbances. The study managed to achieve precision landing and take-offs using an infrared radiation (IR) camera. Furthermore, different control methods have been discussed in this area of research, and Fareh and Rabie[102] proposed two control methods: the centralized control strategy and the decentralized control strategy. Centralized control strategy considered the system as one unit, and a decentralized control strategy considered mobile manipulators as two separate subsystems being the mobile base and robotic arms, as discussed in [103]. A research firm[104] mentioned that industrial and commercial markets are now focusing on replacing the human labor force with drones equipped to perform human tasks or imitate human arms and that there is an increasing demand for drones to perform specific hands-on operations. An example of a dual-arm hexacopter is shown in Fig. 8. The developers stated that it could perform a variety of tasks such as to grasp and carry different cargo, join units or things, turn dials, flick switches, and cut cables[104].

Fig. 9 shows another example of a drone with a sidearm kit. The developers[105] claimed that the sidearm is a robotic arm that clips onto the drone to provide aerial manipulation capability. Furthermore, they stated that the sidearm kit is compatible with Da-Jiang innovations (DJI) Phantom 3 and 4 drone models. The kit has claws made of carbon fiber talon-like, which are used for grasping and carrying cargo. The weight of the arm-kit was estimated to be around 135 g.

6.1 Individual control of drones with robotic arms

There are different types of individual drone uses. Some examples of drone uses are medical assistance shown in Fig. 10 and cargo transportation as shown in Fig. 11. Drones with robotic arms perform different aerial manipulation, which is another form of configuration in robot control.

Fig. 8 Drone re-printed with permission with permission from PRODRONE[104]

Fig. 9 Side robotic arm-kit compatible with DJI drones, registered trademark of GearWurx, re-printed with permission from GearWurx[105]

Aerial manipulation robots can be used to carry a rod-shaped object using two multi-rotor drones with robotic arms, as stated in [107]. Multi-rotors[108] are preferred because they can easily access a three-dimensional work-space, and the execution of tasks is limited to the payload. Additionally, Wu et al.[109] highlighted that a co-operative approach is promising for aerial manipulation robots with limited payloads. The operation of cooperative, multiple mobile platforms required considerations on motion synchronization and the overall system's stability[110]. Moreover, there has been an extensive study[111] on stationary or ground mobile manipulators, which made it possible to control two or more units simultaneously. This addressed aerial manipulation control problems. To validate the aerial cooperative manipulation, Jimenez-Cano et al.[112] carried out an autonomous flight test of two cooperative aerial manipulators carrying a rod-shaped object. The drone bases were controlled regardless of the effects of uncertainties brought about by the robotic arm and the target object itself. The study claimed that the proposed methods were indeed suitable for aerial manipulation and that simulation demon-

Fig. 10 Medical drone re-printed with permission from [106]

Fig. 11 PD6B-AW-ARM transporting ability re-printed with permission from Prodrone

strated that the proposed controller is robust against parametric uncertainties and external disturbances.

The following aerial manipulation controllers are briefly discussed in this section: compliance control scheme, interconnection and damping assignment passivity-based control (IDA-PBC), cascade control, and hierarchical motion control.

6.1.1 Compliance control scheme

A compliance control scheme is characterized by three layers, as shown in Fig. 12, and as mentioned in [113]. The scheme has a motion planner used to achieve the desired velocity trajectories for the end-effector, and an impedance filter conferred a compliant behavior to the system. The motion controller tracked the output reference values from previous layers. The effectiveness of the algorithm was tested in Matlab/SimMechanics© simulation environment, and the comparison between the forces showed that the impedance filter allowed for a reduction in residual forces.

6.1.2 Interconnection and damping assignment passivity-based control (IDA-PBC)

Mello et al.[114] focused on analyzing aerial manipulation dynamics and controller, which is suited for a quadrotor with an n-link manipulator in a free motion in space using the IDA-PBC method. The controller was designed with the manipulator placed at any position while ensur-

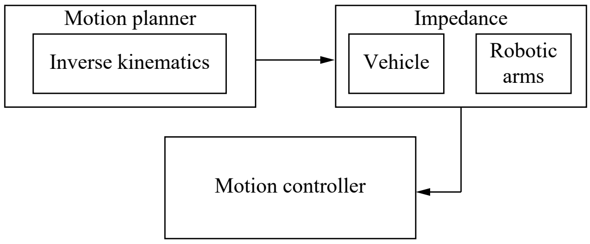

Fig. 12 Block diagram for the compliance control architecture

ing global asymptotic stability. It used the Lagrangian formulas and Hamiltonian formulas for the control of the under-actuated mechanical systems. This helped the end-users to comprehend the real complexity of controlling aerial manipulators in a cyclo-passivity instead of standard manipulators. As a result, the study affirmed that the designed passive controller proved to be stable and simplified many highly complex nonlinear control problems.

6.1.3 Cascade control

In [114], a cascade control was designed for a quadrotor serially coupled to a robotic arm with dual-loop systems. The inner-loop system is considered a partial feedback linearization controller resulting from the Lie derivative. The outer loop as a kinematic controller tackled any uncertainties from the feedback linearization approach. Two controllers in parallel were considered: the backstepping controller for UAV motion and the PID controller for the robotic arm. The paper took into account the center of mass of the UAV, which is greatly influenced by the end-effector. The cascade control strategy helped to track desired trajectories for the end-effector while maintaining stability for the whole system.

6.1.4 Hierarchical motion control

The hierarchical motion control scheme or architecture for UAVs with a manipulator is shown in Fig. 13, as discussed in [115]. The controller has two layers: an inverse kinematics layer as the top layer and a motion control layer as the bottom layer. The study showed the effectiveness of this approach in the presence of disturbances. It has also proved that it is possible to make a conceptual separation between quadrotor position and orientation. The hierarchical controller was proposed based on an inner/outer-loop system with vision-based controllers. The bottom layer, which is the motion controller was the UAV controller which computes the thrust forces and references flight angles. Furthermore, the study claimed that a dynamic model for the whole system was developed (UAV and the manipulator) with a Cartesian impedance controller to cope with contact forces and external forces. The simulation results showed that the controller is effective even in the presence of model uncertainties.

6.2 Control for cooperation of drones with robotic arms

This section reviews the coordinated control of multiple aerial vehicles with manipulators. Fig. 14 shows an aerial manipulator with multi-DOFs that can carry out a pose manipulation of rod-shaped objects. These aerial manipulators can be used to perform cooperative tasks.

Coordinated control of multiple aerial vehicles with manipulators has raised scientific interest due to their wide applications and ability to perform complex tasks impossible for single aerial robots[117]. Leica et al.[118] stated that serial manipulators present limitations such as payloads, complex missions, and cooperative transportation of large and heavy cargo. The following methods of control are discussed.

6.2.1 Adaptive sliding-mode controller

Lee et al.[119] presented planning and control synthesis for collision-free cooperative aerial transportation. The cooperation setup consisted of a hexacopter and a 2-DOF robotic arm controlled by an augmented adaptive sliding mode-based controller. They presented a rapidly exploring random tree star (RRT*) as a motion planning algorithm, and for dynamic movements of the system, they used dynamic movement primitives (DMPs). Moreover, they claimed to have used an RRT* with the Bezier curve for the robotic arm's path planning. Finally, they presented an experiment in user-guided command and RRT* planned trajectory, and it claimed to have shown satisfactory results in object manipulation.

6.2.2 Dynamic surface-based control

Lee and Choi[120] presented a dynamic surface-based control for a drone equipped with a 2-DOFs robotic arm. They mentioned that it used an altitude and attitude

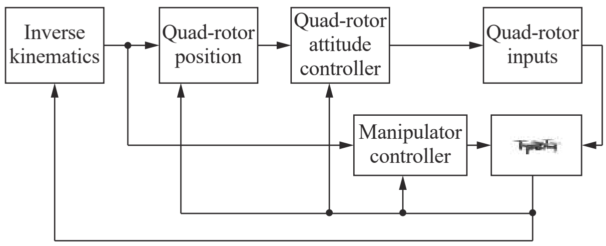

Fig. 13 Block diagram for the hierarchical control architecture

Fig. 14 Aerial manipulators with multi-DOFs[116]

control-based method together with multiple sliding mode control methods based on position control. Conclusively, it stated that their simulation results proved that the system and control methods are stable and have convergence in error tracking.

6.2.3 Image-based visual servo (IBVS) control

Bourquardez et al.[121] used an image-based visual servo control scheme to regulate the position of a quadrotor vehicle. This paper investigated and demonstrated the effectiveness of the controller on autonomous aerial vehicles and aerial manipulators. The servo controller has two loops. One is the inner loop, which is an altitude loop controller using inputs from the aerial vehicle′s onboard sensors like gyro meters and accelerometers. The other is the outer loop, which is relied on the feedback from the image sensors. They claimed that designing a classical IBVS transitional control law ensures good system behavior.

6.2.4 Velocity and curvature constraints approach

Since aerial manipulation is an entirely new field, different approaches have been considered. One approach used velocity and curvature constraints for aerial manipulation in the presence of obstacles[122]. It is stated that a simple curvature-constrained harmonic potential flow and streamline-changing algorithm generate smooth paths used for obstacle collision avoidance in aerial manipulation in real-time. This algorithm was tested using a load-carrying, custom-made aerial manipulator, which is proved to be effective.

6.2.5 Multi-rotors motion controller

Kim et al.[107] mentioned before, a pose manipulation of a rod-shaped object using two aerial manipulators with multi-DOFs was investigated. Both motion control and planning methods for aerial manipulation are presented. They claimed that regardless of disturbances from the robotic arm, multi-rotors are controlled using the extended high-gain and disturbance observers. For the safety of cooperative aerial manipulation, they claimed that it used motion planners. Also, they designed a unilateral constraint to impose collision avoidance between the target object and aerial manipulators. Ultimately, simulation results were validated by a successful autonomous aerial manipulation experiment.

7 Results analysis

Table 2 shows a summary of cooperative control for fixed-base manipulators, mobile manipulators, and drones with robotic arms. These are shown with respect to types of mechanisms, types of controllers, methods of control, tasks, major advantages, and industries where the robots are found. These studies are chosen to give a sample of studies on cooperative manipulators with mobile or drone bases with a variety of assigned tasks and industries where they are found.

7.1 Cooperative fixed-base manipulators

For cooperative fixed-base manipulators, there are several studies on dual-arms, but there are also considerable studies on cooperative manipulators with more than two arms. Most of the controllers used impedance controllers or hybrid controllers. These types of controllers are also extensively used for single manipulator control. Therefore, controllers normally do not vary too much between single manipulator and multiple manipulators control which can subsequently mean that robot control is influenced more by robot interaction with the environment, where robots other than themselves can be found. The control method is about the way the assigned task is being performed and how the robot is interacting with each other and with the environment to perform the assigned task. In most cases, it is based on position-force control, impedance control, and some computational methods. The tasks are greatly influenced by the overall requirement of the job assigned to the robot and the mechanism types assigned to perform it.

Fixed-base cooperative manipulators are mainly in used manufacturing and assembly industries because the environment is highly structured. The workpieces for the robots to interact with are designed to be automatically brought to them. This kind of work arrangement is welcome in such industries to minimize the robot′s reachable workspace to maintain the safety of the human workers present on the manufacturing floor. In the future, when robots become more dexterous and more intelligent, interaction with human workers can be of lesser issue to worry about. Such that cooperative manipulators can become mobile instead of fixed base.

Another advantage of fixed-based cooperative robots is that they help in implementing dexterous manipulation, grasping, and robot interaction with other robots and humans in the environment. These aspects of manipulation and interaction need to be properly implemented, observed, analyzed and optimized before the manipulators can be confidently attached to ground or air moving bases. The future of grasping, multi-fingered interaction, tactile sensing, haptics, etc., are some of the immediate challenges in cooperative fixed-base manipulators that need to be addressed before we can confidently make them roam around freely and interact with humans and structure environments.

The methods of control for fixed-base manipulators mostly deal with position and force control because they are expected to interact with the environment by touching, manipulating, and sometimes penetrating. This is different from most manipulators with mobile or aerial bases where robot-environment interaction is not as extensive as in fixed-base manipulators. One could say that the problem of robot-environment interaction for fixed-base manipulators is more immersive in terms of forces and manipulation task coordination compared to robots with mobile or aerial bases.

Table 2 Results analysis

Types of mechanisms	Types of controllers	Methods of control	Tasks	Major advantages	Industry
Two 3-DOFs robotic arms, one base[81, 123, 124]	Adaptive Jacobian control	Adaptive synchronized tracking control	Painting, welding	Stability of the system (discrete time domain)	Manufacturing
6-DOF robot dual-arms[83, 125–127]	Impedance control	Centralized impedance control	Grasping large card-box	Autonomous problem solving	Packaging industry
Under-actuated manipulators[75, 128–130]	Hybrid control	Motion, squeeze force control	Assembly of structures, manipulation of flexible loads	Load tracking	Assembly industry
Cooperative robotic arms[76, 131–133]	Hybrid position/force control	Position, force control	Assembling multiple parts	Trajectory tracking	Assembly industries
Multiple manipulators[79, 134, 135]	Decentralized, adaptive hybrid intelligent control	Multi-input multi-output fuzzy logic engine	Multi-fingered object manipulation	Position, orientation and error tracking	Manufacturing industries
Cooperative manipulators[77, 136–138]	Multiple impedance control	Augmented object control	Object grasping	Path, performance tracking	Assembly factories
Wheeled mobile robots[87, 139, 140]	Fault-tolerant cooperative controller	Input-output feedback linearization control technique	Surveillance	Autonomous re-assigning of tasks	Military
Mobile bases[88]	Slide-mode formation controller	Visual-based system	Mapping, research, and rescue	Vehicle stabilization, coordination	Military, disaster management firms
Mobile bases[89, 141, 142]	Target-tracking controller	Distributed Kalman filter, flocking control	Cooperative classification	Track moving object	Industrial factories
Multi-mobile robots[90, 143–145]	Visual observation, fuzzy logic controller	Visual observation	Parcel delivery, packaging	Convoying system	Packaging industry, postal firms
Wheeled robots[53, 146–148]	Cluster-space controller	Multi-robot formation control	Transportation, manipulation of large objects	Single operator, effective command, and monitoring	Hazardous environments
Two wheeled robots[54,149–151]	Rigid formation motion controller	Rigid-closure method control	Transportation of rigid objects	Precise manipulation of rigid objects	Transportation systems
Wheeled mobile robots[55, 142, 152]	Dynamic control law (sigma processes)	Formation control, trajectory control	Tracking targets, troop hunting	Accurate formation control	Military, wildlife
Wheeled mobile robot[56]	Force controller	Idealized joint unit (IJU) control	Human-robot interaction, object manipulation	Generates accurate torque with assigned inertia and viscosity	Transportation industry
Hexacopter with 2-DOF robotic arm[119, 153–155]	Adaptive sliding-mode controller	Rapidly exploring random tree, dynamic movement primitives	Disaster monitoring	Collision free cooperative manipulation	Military, search, and rescue firms
Drone with 2-DOF robotic arm[120, 156–158]	Dynamic surface-based control	Multiple sliding mode control	Electric, power inspection	Stability error tracking	Power industry
Quad-rotor vehicle[121, 159–161]	Image-based visual servo (IBVS) control	Classical IBVS transitional control law	Aerial photography	Position regulation	Military, media firms
Aerial manipulator[107, 162–164]	Multi-rotor motion controller	Extended high-gain and disturbance observers	Cargo transportation	Collision avoidance	Military, parcel delivery factories
Aerial Manipulator[122, 165–167]	Velocity curvature constraint approach	Curvature constrained harmonic potential flow streamline changing algorithm	Cargo transportation	Real-time obstacle collision avoidance	Military, search and rescue

7.2 Cooperative mobile manipulators

For cooperative mobile manipulators, there has been an intensive study on different types of mobile manipulators such as wheeled robots and tracked robots. The majority of the controllers used slide-mode controllers and target-tracking controllers for mobile robots; this is mainly because mobile robots use formation and trajectory control and avoiding collisions.

The industries of cooperative mobile manipulators are similar to cooperative mobile base robots because of their common ability to explore far, unstructured environments. However, one can say that the advantage of mobile manipulators is that they combine the ability of fixed-based manipulators with mobile bases. It results in a combined capability of exploration and manipulation that increases the ability of the cooperative robots to perform assigned tasks. The advantages of the cooperative fixed-base robots discussed above, as well as the advantages of cooperative mobile bases, generally apply to the cooperative mobile manipulators.

The major research challenge in this platform can be the coordination between the manipulator that is lighter and dexterous and the mobile base that is heavy and less agile. The challenge is to combine these two robots with significantly different characteristics to perform the assigned task in a holistic, well-coordinated approach; this is especially challenging when the robotic arm is interacting with the environment while the mobile is simultaneously struggling to localize itself in an unknown environment. Most of the control strategies used are a combination of fixed-based manipulators and cooperative mobile bases.

This may be a good platform to investigate a seamless fusion between direct force and motion control required for robot-environment interaction and machine learning and artificial intelligence required for environment exploration. In most cases, switching between direct control and machine learning is the usual approach such that one will take over and the other one will give way. In this platform, it may be required that both will be actively utilized in a well-coordinated, seamless fusion of the two control strategies.

A visual-based method of control is useful in mobile bases control, where machine learning and artificial intelligence are becoming a growing area of research in robot development enabling cooperative robot′s human interaction and reducing accidents at the same time. Visual-based methods also aid operators in controlling many cooperative robots simultaneously. It is evident that cooperative mobile bases are used mainly in object manipulation, search and rescue operations, surveillance, and manufacturing. Studies have shown that mobile manipulators are capable of re-organizing themselves in a formation that is operated by a single pilot. This could be one of the reasons why most cooperative mobile robots are used in different industries, including military, packaging, and transportation. The cooperative robot′s system has proven to be efficient. However, there are also setbacks on the system: Where the extra safety measures are deployed, the cooperative robots′ speeds are limited to embrace safety, there is still a need for humans to supervise autonomous robots to observe any irregularity in tasks performed and in the cooperative setup itself.

7.3 Cooperative aerial manipulators

The survey shows that aerial manipulation and development have grown exponentially in recent years. Some drone bases found during the review are quadcopters, hexacopters, and octocopters. Furthermore, it shows that in recent developments, researchers attached robotic arms to drones′ bases for aerial manipulation. Different controllers are used in aerial manipulators, including multi-rotor motion controllers, adaptive sliding mode controllers, and dynamic surface-based controllers. Machine learning is also used in aerial manipulators especially during human-drone and drone-environment interaction, in search and rescue operations, entertainment, and power industries.

In this platform, the immediate research challenges can be similar to the cooperative mobile manipulators. However, the aerial base has higher degrees-of-freedom compared to the mobile base and is sensitive to environmental disturbances, especially wind. Furthermore, independent axis control of drones is an emerging research topic looking to increase the dexterity of drones. This ability is highly critical when a manipulator is attached to it. In this case, the dexterity requirement is now added with the coordination required to holistically perform the assigned task on both the drone base and manipulator. The case of two manipulators with drones′ bases can be considered as dual arms with flying shoulders. This is a very effective tool in dual-arm manipulation because it increases the robot′s workspace and the operational area becomes fully spatial.

8 Conclusions

This paper presented a review on cooperative robotic arms with mobile or drone bases. The review showed a range of cooperative manipulation and coordination control. It is evident from the review that aerial manipulation has recently gained increased attention by many researchers. The autonomous cooperative control of aerial manipulators is a growing area of future studies. It is possible that the same control techniques in cooperative mobile manipulators will also be used in aerial manipulators, especially in robot-human and robot-environment interaction, coordination, and vision and anti-collision systems. The most promising approaches for further investigation and refinement are human-aerial manipulator and aerial manipulator environment interaction. Another interesting future direction could be piloting multiple aerial manipulators using brain signals and not remote controllers (joysticks).

The advantages of using brain signals or human drone interaction instead of joysticks are eliminating the joysticks to simplify human-machine interaction and aiding the development of artificial intelligence, increased system reliability and precision, and increased product usage by enabling the system to be used and controlled by disabled operators.

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