A Survey of Wheeled Mobile Manipulation: A Decision Making Perspective

Shantanu Thakar†, Srivatsan Srinivasan⊗, Sarah Al-Hussaini⊕, Prahar M. Bhatt⊕, Pradeep Rajendran†, Yeo Jung Yoon⊕, Neel Dhanaraj⊕, Rishi K. Malhan⊕, Matthias Schmid⊗,Venkat Krovi⊗ and Satyandra K. Gupta⊕*

⊕Realization of Robotics Systems Lab, University of Southern California

Los Angeles, California 90089-1453.

⊗ Dept. of Automotive Engineering, Clemson University

Greenville, South Carolina 29607-5257.

†Email: [shantanuthakar,pradeepunique1989]@gmail.com

⊕ Email [salhussa,rmalhan,praharbh,yeojungy,dhanaraj,guptask]@usc.edu

⊗ Email: [srivats,schmidm,vkrovi]@clemson.edu

Abstract: Mobile manipulators that combine base mobility with the dexterity of an articulated manipulator have gained popularity in numerous application verticals ranging from manufacturing, infrastructure inspection to domestic service. Deployments span a range of information- and physical-level interaction tasks with the operational environment, from inspection to tending and logistics-resupply to assembly. The key capabilities emerge by adding kinematic and actuation redundancies within such articulated mechanical systems. This flexibility, offered by the redundancy, needs to be carefully orchestrated to realize enhanced performance. Thus, advanced decision-support methodologies and frameworks are crucial for successful mobile manipulation in (semi-) autonomous and teleoperation contexts. Given the enormous scope of the literature, we restrict our attention to decision-support frameworks specifically in the context of wheeled mobile manipulation. Hence, we present a classification of wheeled mobile manipulation literature while accounting for the diversity and intertwining of deployment tasks, application-arenas, and decision-making methodologies with an eye for future avenues for research.

1 Introduction

For over a half-century, robotic systems have been deployed to extend the reach of humans in performing dumb, dull, dirty, and dangerous tasks in numerous application settings. Early deployments featured largely static, fenced, and permanently integrated solutions with specific customization for particular operations. However, in the Industry 4.0 era, robotics has evolved to provide flexible, reconfigurable, intelligent mobility and manipulation capabilities close to humans.

Mobile manipulators offer an evolution in robotic system architectures [1] that facilitates graduation from mere automated systems to autonomous ones. Such systems merge mobility (offered by the mobile platform) with the manipulation capabilities (afforded by the mounted articulated arm) to create an unlimited manipulation workspace. Mobile manipulators have become popular in numerous *deployment verticals*: industrial (factories, warehouses), domestic (household), outdoor field settings (highway maintenance, earthmoving/excavation to free-flying satellite repair) due to the flexibility they provide in undertaking and assisting a variety of tasks [2–9]. Building on the merger of mobility and manipulation, the *abstracted tasks* comprise relatively broad categories such as inspection, part-picking, transportation, assembly, site-tending, and more. Ultimately, the intersection of deployment application verticals/abstracted tasks in autonomous, semi-autonomous, or completely teleoperated operational contexts results in the seemingly infinite diversity of intelligent mobile manipulation examples.

The application of the robotics (*Sense-Think-Act in real-time*) paradigm forms the underlying basis for an embodiment of intelligence in mobile manipulators. *Sense* encompasses capabilities that help in sensor-based perception of the robot and the surrounding environment; *Think* involves information-processing and decision-making capabilities required for a particular task, and *Act* pertains to the physical realization of intelligent mobile manipu-

*Address all correspondence to this author.

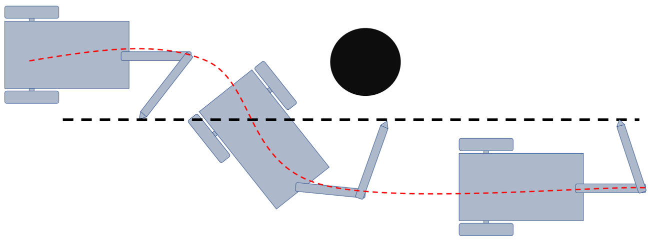

Fig. 1. Wheeled mobile manipulator utilizing alternate specifications of desired end-effector and base trajectories

lation within the environment. In all cases, mobile manipulation entails an underlying cyber-physical/articulated mechatronic system to realize intelligent physical interactions with the environment. Depending on the engendered timescales, this intelligence capability has to be realized via various decision-support methodologies/frameworks categorized as planning (offline, deliberative), control (online, reactive), and human-robot interaction (interactive) frameworks. Ultimately, it is required to close the loop in real-time and the technological constraints (on computation/communication/miniaturization) that enable (or limit) the realizable intelligent behaviors.

1.1 Background and Terminology

Many variants of the mobile manipulator architecture are possible, based on the nature of the mobile bases (rail or XY-gantry mounted system, wheeled/tracked platform, and more) and the nature of the mounted manipulator (number and type of articulations and their actuation, e.g., serial vs. parallel).

Wheeled mobile manipulators are comprised of a wheeled-mobile robot base with one or more mounted manipulator arms [6, 10–12]. They are an important and popular subclass/deployment configuration of mobile manipulators. They offer ungrounded, easy-to-use, adaptable architecture suited for numerous applications. They inherit many typical benefits of redundant manipulators such as expanded workspace (both conventional and dexterous), reconfigurability, improved disturbance-rejection capabilities, and robustness to failure. In addition, they also can: (i) accommodate changes in the relative configuration (by the excess degrees-of-freedom); (ii) detect such changes (using sensed articulations); and (iii) compensate for such disturbances (using the redundant actuation within the chain), while interacting with the environment. Fig. 1 depicts a wheeled mobile manipulator modulating its end-effector motion/force interactions with the external environment while using surplus internal degrees-of-freedom within the system to control the relative configuration/pose. Ultimately, this redundancy proves crucial to enhancing their ability to perform autonomously or semi-autonomously assist a human operator during dynamic interactions with the world. Key factors/considerations to realizing superior performance in mobile manipulators include:

1. **Design Architectures**: The underlying cyber-physical system architecture, with introduced design-freedoms, is crucial – the type, number, location, and actuation of the wheels/articulations within the mobile manipulator modules play a critical role in determining the performance capabilities. Careful selection of the topology, dimensions, and configuration, thus, is crucial in determining the capabilities and overall system performance.
2. **Planning-Control Frameworks**: A planning-control framework is necessary to exploit the "design-freedoms" for realizing the superior intelligent behaviors. Advanced planning/control frameworks are needed to: overcome environmental constraints (e.g., contacts, nonholonomic); resolve redundancy (kinematic and dynamic); minimize singular configurations of the system; modulate physical power exchange with environment (motions and forces) during task performance, and improve robustness to local controller lapses and environmental disturbances.
3. **Human-Machine Interfaces**: Mobile manipulation offers new capabilities to extend human reach. However, the complexity of the underlying mobile manipulation system and physical interactions with the environment require new operational paradigms. Human-robot teaming frameworks with probabilistic sensor fusion (of distributed heterogeneous Spatio-temporal data) with the computational model-based frameworks (both mechanistic- and learning-based) have now emerged. This now affords intelligent decision-support strategies – exploiting the strengths of both humans/robots to improve shared decision-making, control autonomy, and transparency with ever-changing, uncertain conditions.

1.2 Survey Scope

Several surveys on topics related to mobile manipulation have emerged in recent years. Bostelman et al. [13] present a literature survey of mobile manipulator research with examples of experimental applications. It also provides an extensive list of planning and control references as this has been the major research focus for mobile manipulators, which factors into performance measurement of the system. Song et al. [14] discuss the development of mobile manipulators in the aspects of motion planning, coordinating control, and multiple mobile manipulator coordination and presents various problems involved and the methods to deal with them. Youakim et al. [15] present a survey of motion planning algorithms like sampling-based, search-based, and optimization-based motion planners for underwater autonomous mobile manipulators and attempts to answer the tough question "which planner to choose." The state-of-the-art of the most common approaches are discussed, and a set of benchmarks are presented with the aim to provide a comprehensive review as well as a qualitative/quantitative comparison of the algorithms. Moreover, aerial manipulation has been surveyed in [16]. [17] is a textbook that extensively explores the methods of modeling, planning, and control for wheeled mobile manipulators, but mostly in the context of multi-robot cooperative control. Other recent surveys provide high-level insights into the practical aspects of wheeled mobile manipulation. E.g., A survey of the recent advancements in mobile manipulation state of the art and technical challenges with the RoboCup design competition as the focal point was presented in [18]. A review of the system architecture and application space of collaborative mobile manipulators was put forth in [19]. Although these surveys reference contemporaneous mobile manipulator research, they do not discuss or categorize the methodologies themselves – a task which we will attempt here.

However, given the vast amount of literature, we restrict our focus to solely surveying the decision-support methodologies, i.e. *planning-control* and *human-robot interaction* in the context of wheeled mobile manipulation. While design-architectures, perception, learning, etc., are important, we succinctly discuss these topics in the rest of this section (and offer suitable further references for detailed follow-ups).

From the perspective of *design-architectures of mobile manipulators* it is important to factor the contributions of both the *wheeled mobile base* and the *manipulator arm*. The mobility, steerability, and controllability of the overall wheeled base depend largely upon the type, nature, and locations of the attached wheels [20]. Hence, the decision-making aspects of such vehicles need to explicitly take into account the maintenance of the kinematic compatibility conditions. Recent trends highlight a renewed interest in addition of active or passive articulations between the wheels and chassis to ensure kinematic compatibility [21–24]. From a manipulator perspective, a careful selection of the topology (serial vs. parallel, numbers of joints) as well as the structural parameters (link-lengths) and configuration parameters (joint-angles) all affect the ultimate performance of the manipulator individually (as well as part of the mobile manipulator system) [25, 26]. Further readings on design-architecture topic areas available in texts [27–31].

Perception is another important dimension to harnessing intelligence in both *mobility* and *manipulation* tasks - traditionally, a multi-step process (of sensing, signal processing, and cognition) underpins the perception process. Navigation in both indoor- and outdoor settings, as surveyed for wheeled mobile robots [32] are relevant here – as are surveys of further cognitive-processing to develop situational awareness from perception [33]. Worthy of special mention are the adaptations of the *active-perception paradigm* in the context of mobile manipulation in the form of *vision-enabled manipulation* including object recognition, grasping, pose estimation, etc. Detailed discussions on vision technologies necessary for 2D and 3D manipulation for robot manipulators can be found in [34, 35]. Deep learning and other data-driven methods are extremely popular in perception as they provide an intelligent methodology to overcome several key problems in extracting information from sensing. These methods help overcome common disturbances and noise a robot could encounter in processing visual information in its surroundings, as discussed in [36, 37, 37]. Lastly, visual-servoing is often pursued to develop a direct tie between the perception and decision-making processes for robots [3, 38–40]. Specific works addressing the safety interwoven into the perception problems when the robot is operating amongst humans are discussed in the survey [41]. Although most perception algorithms are largely architecture agnostic, literature surrounding perception as applied to mobile manipulators can be found in [40, 42–45].

1.3 Organization of rest of the paper

Sec. 2 presents a description of applications that have the potential to be large beneficiaries from mobile manipulation capabilities while also attempting a categorization based on their dependence on key decision-making capabilities. In Sec. 3, each capability that forms the tenants of the decision-making hierarchy that enable mobile manipulation is presented in Sec. 2. Lastly, in Secs. 4 and 5, the future research directions and emerging opportunities for mobile manipulation are briefly presented. Finally, the Appendix presents a visual categorization and overview of the applications and the methodologies used in this manuscript.

2 Application Deployments

The application perspective offers a convenient approach to developing key performance indices. Identification of quantitative measures and criteria for system-level performance provide key insights that aid with the choice of decision-making strategies. Our emphasis will be on abstracting the performance requirements across applications. We will focus on four representative application verticals that are common deployment venues for wheeled mobile manipulation. Representative mobile manipulators exemplars deployed in various applications discussed in this section are highlighted in Fig. 3. Additionally, a detailed graphical mapping of the literature that specifically addresses all the application verticals discussed in this section is presented in the form of a flowchart in Fig. 2. Further, this flowchart also classifies the literature in the laterals of the particular decision-making aspect addressed, namely planning, control, and human-robot interaction.

2.1 Industrial Operations

Wheeled mobile manipulators are widely used in warehouses and shop floors for object (e.g., tools, parts, packages) transportation which involves picking up objects and dropping them off at an appropriate location or handing it off to a human worker. Additionally, they are also deployed for machine tending, which can be defined as material handling such as loading or unloading and part feeding for machines (e.g., CNC machines). The use of fixed-base manipulators (in small fenced cells or as part of a production line) raises the infrastructure costs and creates challenges for line-balancing. The use of the ungrounded mobile manipulator configuration to empower flexible production lines becomes very attractive. In this subsection, we explore the requirements of a mobile manipulator employed in the context of this industrial operation.

Several mobile manipulators have been used for transportation of objects [46–56]. Transportation of small objects

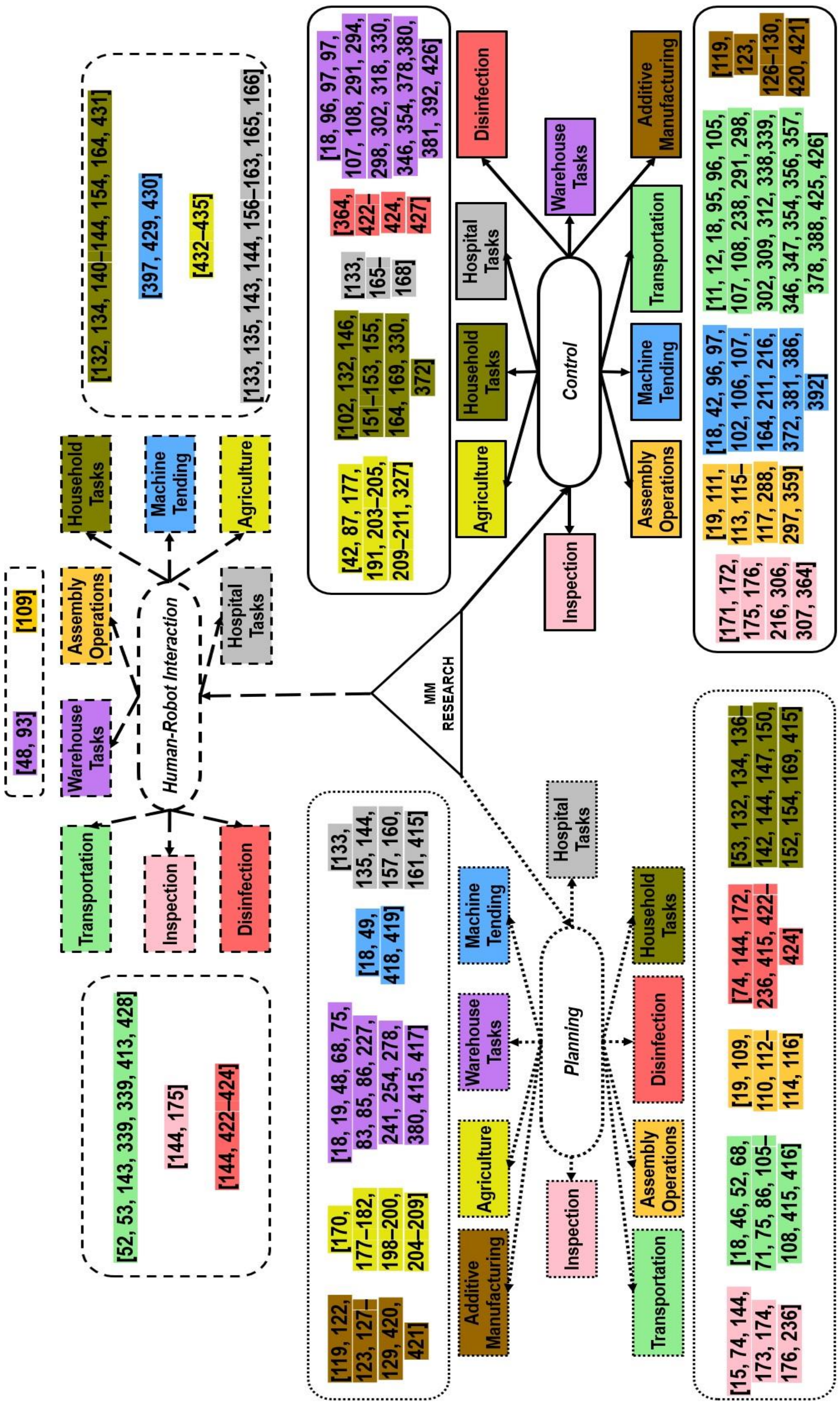

Fig. 2. A Graphical Presentation of Representative Papers in Literature

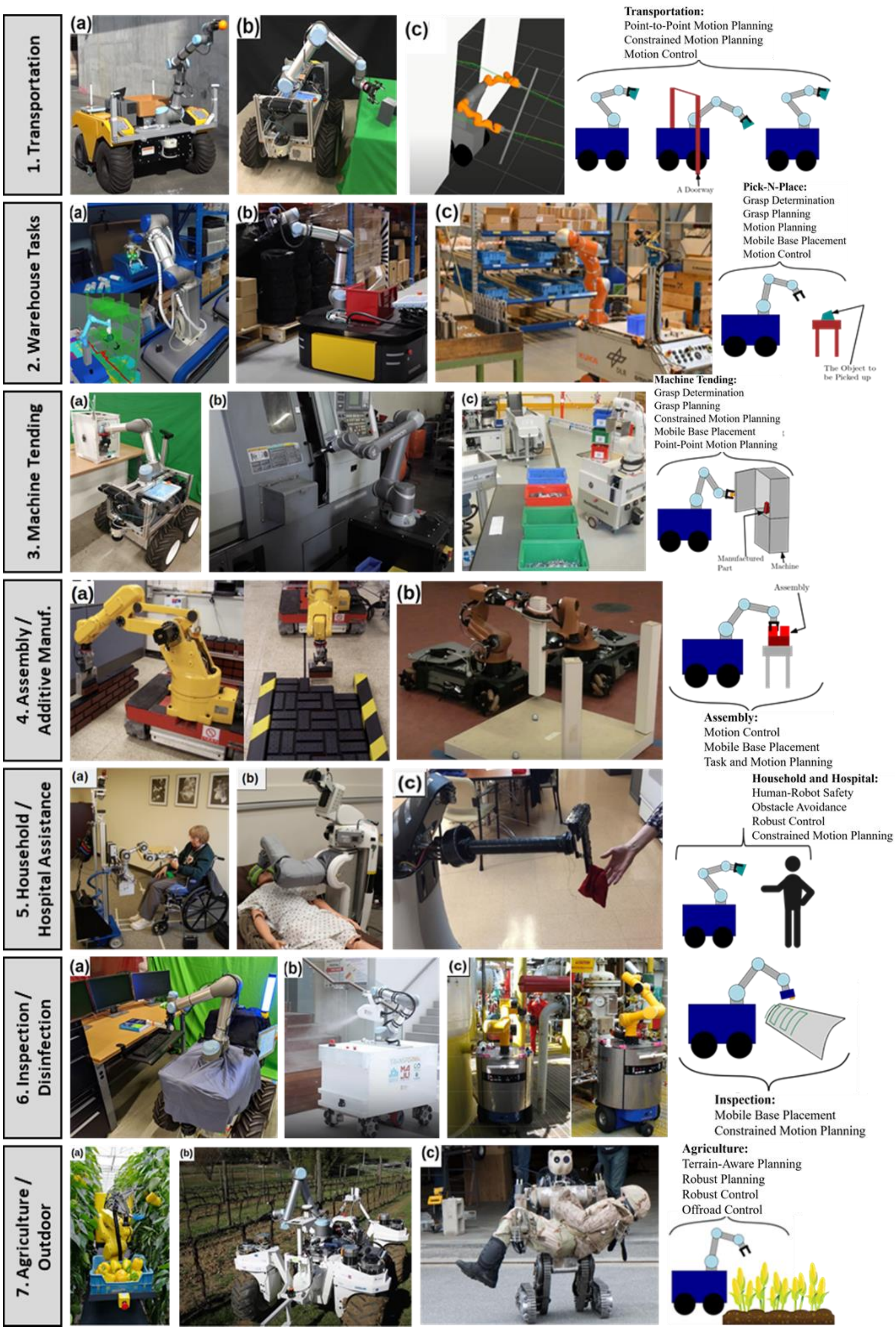

Fig. 3. Exemplary mobile manipulators in various application arenas/tasks from the literature (citations noted in Appendix).

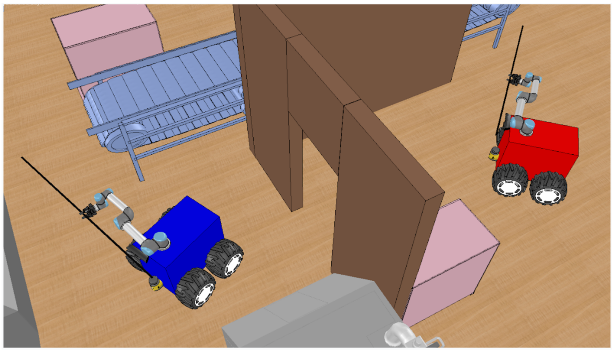

Fig. 4. The mobile manipulator has to carry a long rod through a narrow door [71]

is typically done either by holding the manipulator throughout the entire operation or by securing the object onboard the mobile base. The robot's decision-making is targeted towards only one subsystem at a time – driven by the emphasis on modularity/vendor diversity for the arm and the base. Literature on independent motion planning for the arm and base can be found in [57–64] and [57, 58, 62, 65–70] respectively. On the flip side, in the case of transporting larger objects, such as shown in Fig. 4, the base needs to be aware of the obstacles in the vicinity of the arm and subsequently the object. This creates a need for an integrated/whole-body approach towards decision-making. In [71] for example, a sampling-based method is deployed for the planning of nonholonomic mobile manipulators. In general, any high degree of freedom motion planners [57, 58, 62–64] can be used to determine the solution; however, specific computational speedups would be crucial to support real-time deployments.

In some cases, whole-body decision-making is also required for manipulating small objects during their transport phase, e.g., preventing sloshing in open liquid containers, maintaining task-space orientation of manipulated parts during transport, etc. Researchers have handled these edge-cases by making the planner implicitly also determine the waypoints for the transported object [72–75].

Bi-manual mobile manipulators that mimic humans in mobile manipulation scenarios can use their excessive redundancies to hold an object in place while the base can plan its motion independently [57, 58, 62–64]. Optimization-based motion planning [74] are often deployed for whole-body planning, including for constrained motion planning sub-problems such as the piano movers problem [76].

The industrial applications also motivate an important class of problems pertaining to enhancing manipulator/gripper access while picking parts. Grasp locations on the object can be determined using several existing methods [77–85]. Motion planning has been enhanced for picking up objects with moving mobile bases [68, 86] while factoring in object-pose uncertainty by modulating the gripper speeds [75]. Accurately executing these trajectories where the mobile base and the manipulator move concurrently has led to the exploration of the multiplicity of control approaches [87–91].

Material Handling refers to loading or unloading completed parts from machines such as 3D printers or CNCs as shown in Fig 3.3. Ensuring safety in an unstructured environment, ease-of-use and robustness have been considered as important criteria to apply material handling in real-world applications. Usually, material handling consists of a small set of skills, including but not limited to transportation and pick-and-place. In some cases, it includes skills like opening/closing doors, pressing buttons, and turning knobs. Breaking down the task into unit skills allows for re-utilization at the task level.

In part feeding applications, the usual process is picking up the component, moving towards the corresponding feeder location, and serving it to the feeder. The task itself may differ based on the characteristics of the feeder that is to be serviced. Unlike the relatively independent material handling machines, part feeding machines work together, sometimes as part of the same assembly line, to produce a product. Thus, coordination between multiple feeders and mobile manipulators, efficient task sequencing, and scheduling are important requirements in part feeding applications. The task-level programming method that addresses tasks, skills, and device primitives individually has shown promise [48, 92]. Other aspects such as scheduling and specific machine minutia have been discussed in [93, 94].

Constrained collision-free motion planning and control often play an important role in this application vertical given the robot's proximity to other machining tools, human workers, etc. The mobility constraints that are imposed by the limited knowledge on the kinematics and dynamics of the mobile bases impose a complicated mobility control problem, further enhanced by supplemental safety tasks such as safe and guaranteed dynamic-obstacle avoidance. In [95], a controller is introduced that consists of a behavioral learning layer that redirects the desired trajectory while transporting an object by predicting the behavior of the dynamic obstacles.

The pick-and-place control as a whole for mobile manipulators has been discussed in works such as [96, 97] where factors such as grasping, transportation, obstacle avoidance, and stability have been addressed as a whole. Often this problem is studied in a simplified context by holding the mobile base stationary. Control aspects for sub-problems such as fast pick-and-place, contact dynamics, grasping, etc., have also been explored in the form of model-based control (kinematic/dynamic) [98–100] as well as model-free control approaches [101]. Auxiliary tasks such as intelligent obstacle avoidance, for instance, manipulating doorways, have been studied from a control perspective in terms of architecture and implementation in [102]. The existence of dynamic uncertainties on the manipulator's part while carrying a variable payload adds robust stability control requirements for the system. Further, to handle nonlinearities and uncertainties such as unknown dynamics, parameter errors, etc., adaptive control techniques are often required for such applications as demonstrated by [103, 104]. In [105], the authors have addressed the problem of motion control with obstacle avoidance for transportation jobs while carrying the maximum payload, which can cause significant tip-over stability concerns. Some innovative control methods for heavy material handling have been discussed in [106, 107] where additional mechanical systems such as rollers and outriggers are added to the mobile manipulator, and the control is implemented on the robot's side to accommodate for the mechanical add on. Additional nuances when handling mechanical add-on in the obstacle avoidance and motion control aspects to accommodate for force interactions that are unmodelled in the control design are highlighted by [108].

2.2 Manufacturing and Assembly Operations

Mobile manipulators provide the desired task flexibility and mobility for assembly operations involving large parts. For example, a mobile manipulator can go to a work area to get a part and perform assembly operations on a moving conveyor or build a pallet by stacking widgets in the desired pattern. Several works discuss the specifics of autonomous constructive assembly ranging from assembling furniture to load-palletizing to wall-building [109–112].

Assembly introduces manipulation challenges that involve highly reactive, fast, robust, and micromanipulation/fine-manipulation control. The challenge of integrating high-level strategies with low-level controllers requires dealing with uncertainties. A lot of work has been done specifically in the control domain of mobile manipulation, particularly applied to the assembly application [113–116]. Some modern approaches have decided to forego the complex process of modeling such minute aspects and instead have deployed data-driven approaches for skill acquisition [117].

Additive manufacturing is a process in which parts are built by adding material layer by layer [118]. It has numerous advantages, such as the capability to build complex parts, reduced tooling, quick prototyping, less material wastage, and more. However, one of the major limitations of additive manufacturing is the trade-off between the part size and the setup cost [119]. As the part size grows, the setup cost also increases, which usually puts a restriction on the part size. Thus there is a need to develop a cost-efficient setup to perform additive manufacturing at a large scale. Mobile manipulators have a theoretically unlimited workspace and hence could serve in this space effectively. They can be used in additive manufacturing to build large-scale parts without any size restrictions [120, 121]. Most importantly, the mobile manipulator setup cost will not increase with the size of the built part. Literature that highlights the capabilities of mobile manipulators in this space shows their application in facets such as building large-scale parts [122], building a pipe of infinite length [121], etc.

The importance of high-performance control, estimation, and planning when it comes to deployments in this space is highlighted in [123]. It is essential for the robot manipulator to perform robust disturbance rejection control [124–126] based on the feedback from the build process and the deposited material. Additionally, the motion control itself is extremely time-sensitive, and hence a very reactive and dynamic trajectory control algorithm is required to track the Spatio-temporal references. Due to the high interest in the advantages robotics can bring to the additive manufacturing space, there have been several works published in this area [119, 127**?** –129] Planning challenges such as continuous replanning, optimal mobile base placement, and constrained motion planning also important in this application vertical.

2.3 Service and Assistance Operations

The usefulness of mobile manipulators is quite apparent in service tasks in home and hospital environments. Several applications such as disinfection[130], providing therapeutic assistance[131], administering medications[132], elderly care[133], disability assistance[134], etc. can be envisioned. Utilizing both mobility and dexterity, they can take over or assist humans with day-to-day tasks, similar to how humans perform them.

The home and hospital environments are typically more unstructured compared to an office or industrial setting, making it challenging for robots to navigate and perform manipulation tasks safely and efficiently. The dynamic and ever-changing environment needs to be handled in real-time, which increases the need for reflexive and reactive behavior. Most everyday tasks in this space mainly involve pick & place operations and forceful interactions, which require capabilities such as target identification & localization, safe & fast navigation, and object manipulation. [53, 131, 135–144] are some works which demonstrate mobile manipulator robotic platforms performing tasks within these environments. These papers cover a variety of tasks done by assistive mobile manipulators such as fetch and carry, tidying-up, cooking, dancing, serving, etc. Many of these works, experiments are being conducted in nursing homes, elderly care facilities, as well as regular homes, with old people and people with disabilities as the beneficiaries. The goal is to provide support for independent living, remote care, and household tasks [131, 139–143].

There are many complex tasks in these situations that do not fit into object pick-up and placement operations. Capabilities such as opening doors and drawers, cleaning surfaces, pushing and pulling beds are fundamental for operating in these environments [145–148]. People envision mobile manipulators to do complex cleaning tasks in the house, which present floor-cleaning mobile robots cannot perform. Mobile manipulators can use their arms to use human tools and perform dusting, scrubbing, wiping, mopping, sweeping of different surfaces and objects within the house [149, 150]. There have also been some works on using mobile manipulators in the cooking domain [150, 151]. In [152], a look into force-inclusive motion control for cooking applications is explored. Mobile manipulators can also help in organizing different items in the house, such as shelves such as libraries [153]. Force control is necessary for opening/closing doors/drawers, manipulating taps/switches, etc. in a mobile manipulator [102, 154].

Patient-caring tasks such as telenursing [132, 155–157] requires specific capabilities, which include safe mobility of the robot, capability of light- to medium-duty manipulation tasks, safety in close proximity to and touching humans, facilitating audio/visual communication between a nurse and patient, etc. Tele-operated mobile manipulators are especially useful for nursing and telediagnosis of quarantined patients, which can limit health care workers' exposure to dangerous microbes [158]. It can also help to expand the caregiving capacity of a hospital very fast whenever a need arises. Work reported in [159, 160] describe a smart hospital ward management system with a mobile manipulator which can perform drug distribution and other tasks. [134] demonstrates a mobile manipulator, collaborating with a robotic bed to provide physical assistance to patients with disabilities. Several assistive robots are studied specifically for people with disabilities [142, 143].

Apart from physical assistance, mobile manipulators are often deployed to be socially assistive robots as well, to provide nonphysical assistance to human users through social interactions. There are multiple applications for such robots, ranging from aiding children and elders with autism to rudimentary tutoring for special needs kids to help out teachers [161, 162]. Safe human collaboration is a very important aspect here as tasks such as handing over things to humans are high-risk operations [163]. This raises extreme robustness requirements as any safety breach is potentially extremely harmful, as demonstrated by [164]. Accurate end-effector force control continues to be extremely important here, despite challenges such as lack of tactile feedback in many cases [165]. Several aspects of control in regards to these constraints are discussed and studied in [166–168].

2.4 Operations in Offroad Unstructured Environments

Mobile manipulator deployments to support precision agriculture practices have proven to be one of the most effective ways to significantly reduce the negative impact of farming on the environment [169]. Agricultural operations serve as a representative application arena to highlight beneficial deployments of mobile manipulators in an offroad/unstructured operational setting. However, the applicability in other unstructured application environments such as nuclear inspection, disaster response/rescue, and other terrestrial/extraterrestrial fielded missions should be readily apparent. These environments are often unmapped (or poorly mapped with significant uncertainty), creating significant navigational challenges and necessitating advanced controls[170, 171]. Oil/gas and nuclear power industries heavily rely on mobile manipulators for inspection purposes as the job is harmful to humans in many cases [172, 173]. Insights into the system architecture and requirements in these specific sub-applications can be found in [174, 175].

A major role of mobile manipulators in agriculture arises in the areas of weed/pest killing, targeted spraying, and harvest picking. For example, weed control mobile manipulators perform targeted elimination of weeds using methods such as controlled spraying, electrocution, laser targeting while covering large areas of farmland as fast as possible. Task-specific customization is often pursued – both in the initial design and in the online control – to overcome variability in the nature of fielded tasks as well as a need for computationally efficient yet robust decision-making processing. Fig. 5 shows some of these machines taken from literature. Similarly, one can find several architectures that are deployed and pursued based on which specific type of crop the mobile manipulator is designed to handle, as shown in [176–181].

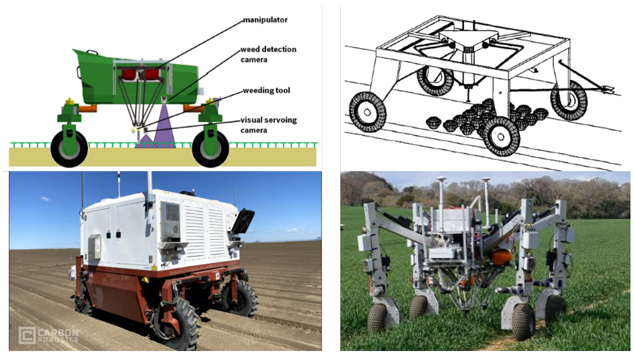

Fig. 5. Weed control/killers mobile manipulators, clockwise from top-left. 1. 'BoniRob' stamps the weeds as they get detected [189]. 2. 'Patchwork' electrocutes weeds post detection [190]. 3. 'Dick', a robot by Small Robot Company [191] also electrocutes weeds. 4. A weed killer robot by Carbon Robotics [192].

Deploying task-specific designs is not unique to the agricultural field – disaster response robots often need very specific mobile manipulators depending on the type of environment, operating conditions, manipulation target, etc. (see Fig. 3.7.c). Task-specific designs as it pertains to inspection and radiation detection in nuclear plants is a prime example of such a case [182, 183]. Mobile manipulators used for rescue that perform tasks such as getting over unknown steps, navigating dense urban environments, opening doors, and operating in chaotic conditions are presented in [184–188].

The robot localization problem plays a very important role in aiding mobile manipulator decision-making hierarchy and is often solved with relative ease in indoor industrial applications using Simultaneous Localization and Mapping (SLAM) [193] due to the ability to have some form of structure or control on the environment. However, in the case of outdoor settings, vision-based methods are challenging due to the where the complexity of problems such as lack of constants in the environment that could potentially serve as landmarks. Even though there have been studies that deployed SLAM in these applications [194], in outdoors, localization of the robot is performed using Global Positioning System (GPS) [195] or ad-hoc sensor systems such as Ultra-Wide Band (UWB) [196], etc. The localization part is also complicated even in certain indoor settings such as agricultural greenhouses since it suffers from the same uncertainty problems that make vision methods difficult, but at the same time, satellite navigation techniques cannot be used. Hence, in many greenhouse settings, the mobility aspect of the mobile manipulators is handled through the use of rails [197, 198]. There is also some work on wheeled mobile robots [199]. The initial step in every single task before the decision-making hierarchy of the robot takes over would be the vision problem of identifying and localizing objects of interest which are addressed in works such as [200, 201].

Safe navigation is essential in agriculture to minimize the impact on the soil and avoid crop damage since the error margins are very small [202]. The paper [203] proposed a robust navigation technique based on cost maps and also presented a framework that can make the inculcation of such techniques to tailored environmental situations. The applicability of this framework using popular middleware such as Robot Operating System (ROS) is also presented. An extension of this work [204] also went on to propose parameter tuning algorithms that close the gap of uncertainties in the robust navigation techniques by making them more adaptable to robot architecture and environmental condition changes. A review of mobile agricultural robotics covering several aspects of planning, manipulation, and design has been presented in [205]. In order to handle the ever-changing environment (growing plants, lighting, weather, etc.), [206] studied an aerial-ground robot combination for deployment in fields wherein the aerial robot maps the field often, and the information is transferred to the ground robot. Similarly, [207] presents several aspects of vision and planning, which is further reinforced by application towards mobile manipulator based strawberry picking application. Several other studies that can explored for safe and robust planning can be found in literature [208].

In terms of the control capabilities for outdoor settings, the biggest focus is on robust control of both the base and the arm to deal with terrain irregularities, deformations, slips, dynamic obstacles, and sensor noise. In agriculture, any error in its trajectory tracking could lead to regular damage of crops, which in summation could lead to a big loss to the farmers. The work presented in [209] explores a systematic design and control architecture development for heavy material handling mobile manipulators that can handle parametric perturbations and uncertainties. Performance comparison of control strategies for existing agricultural mobile manipulators based on various sensors is presented in [190]. In general, control strategies focused on picking objects for mobile manipulators [42] and offroad navigation of unmanned ground robots [210] can be translated to agricultural applications as well. A comprehensive review of agricultural robots in field operations can be found in the two-part study presented in [211, 212].

Given the variability in design, it is often difficult to utilize general off-the-shelf solutions for such applications. For blank slate design, there have been some studies that have addressed the question ”which abilities are necessary to solve particular tasks autonomously?” and discussed how they could be converted into a control architecture in general [213] and in particular to mobile manipulation [214]. Systems that are goal-oriented and the structure of their control architecture differ based on their expected behavior and/or the environment they operate in, as demonstrated by [215, 216]. Control strategies such as dynamic obstacle avoidance [217, 218] need to be adapted for off-road operation in unstructured environments, such as by inclusion of wheel slip [219] and non-rigid terrain adaptation [220].

3 Decision Making for Mobile Manipulation

Decision-making helps to close the loop between the sensing/perception and action in intelligent robotic-systems with various associated nomenclature at the various deployment stages. Coupled with extent of feedback between sensing and action, this continuum ranges from motion-planning/open-loop control methodologies used primarily in offline settings to various forms of online-replanning/closed-loop control suitable for deployments in online settings to address dynamical ego-system and environment.

Since its introduction in the 1980s, the configuration-space [221] approaches have helped create the abstract notion of configuration/state of the system and associated choices of extended vs minimalistic representations. Notions of spatial contiguity (free/obstacle) and temporal continuity (continuous/discrete) ascribe additional qualitative aspects to the underlying state and motions defined as the sequence of states. *Motion planning* for the dynamical system (mobile-manipulator) then becomes a computational problem of finding a sequence of actions to move from an initial state to a goal state in the presence of spatiotemporal constraints. Such spatiotemporal constraints arise naturally due to the dynamics within the environment and most certainly for the dynamical system engendered by the mobile-manipulator. A wide diversity of constraints can ensue based on extent of mobile-manipulator/environment coupling as well as spatial- and temporal-coupling (ie. reducibile to only spatial or only temporal).

Despite the existence of these spatio-temporal constraints there remains enormous redundancy and thence choice for selection of the motion-plan - this paves the way for creation of decision-making frameworks. At their core, such decision-making frameworks are based on the ”design-optimization paradigm”: systematic creation of choices, systematic evaluation of choices and systematic elimination of choices. In particular, the addition of a parametric capability facilitates the leveraging of computational support to address problems of ever-increasing size and scope (as we will note). Further, varying grades of planning/control are possible based on the extent of reliance on sensing (ongoing information gathering within the environment) versus models (pre-existing information about the environment).

3.1 Motion-Planning for Mobile Manipulation

There is a significant body of literature in motion-planning for mobile manipulation that came to the forefront in the late 1990s and is captured in SURVEYS such as[14, 15, 18] as discussed in Sec. 1.2. As a quick aside, a disambiguation is necessary between the often interchangeably used “motion planning” and “path planning”. Whereas path planning only generates a path within the configuration space, motion planning generates time-indexed motion trajectories. Inasmuch path-following only requires spatial-feasibility (e.g. obstacle avoidance) while motion-planning requires compatibility with spatiotemporal constraints (engendered in dynamics of both robot and environment). It is also noteworthy that ultimately any path-planning effort requires a final time-parameterization into a motion-planning exercise prior to deployment.

In the couple of decades since the principal enhancements have come from multiple perspectives: (1) more complex mobile manipulators (larger configuration spaces), (2) deployed in more diverse application settings (greater spatiotemporal constraint complexity), (3) availability of new theoretical/algorithmic tools (sampling based methods, kinodynamic planning), and (4) triple convergence of computing (GPGPUs) communication (distributed), miniaturization (embedded controllers) that has permitted the tackling of larger-scale problems in more real-time settings.

3.1.1 Task vs Motion-Planning

The combined controllable degrees-of-freedom within the kinematic-chain (from both mobile base and the articulated manipulator) presents the mobile manipulator design-architecture the opportunity to address very complex tasks. However, resolving the redundancy (internal/external) is crucial to realizing this potential. As the complexity of overall mobile-manipulation process increases, a two-stage hierarchical approach is often pursued: (i) task-planning/breakdown into a series of tractable motion-planning sub-tasks and their sequencing; (ii) motion-planning of the high degree of freedom mobile manipulator within each sequenced task. It is noteworthy that the two steps (task- and motion-planning) are closely-coupled and should be solved concurrently but are addressed separately from a computational-tractability perspective.

Such task- and motion-planning sequencing issues exist for any robotic manipulator (or subsystems) performing sufficiently complicated tasks over a sufficiently long time-horizon. However, a breakdown along the lines of mobile-manipulator subsystems (mobile-base vs manipulator vs gripper or combinations) or along the nature of the manipulation-task (transportation vs grasping) feature prominently in the literature.Some of the earliest efforts of Wolfe et al. [222] focused on a fixed hierarchical partitioning of task- and motion-planning for mobile manipulator. In more recent times, a more flexible contingency-based partitioning of task and motion planning, combining perception systems with human knowledge, has been pursued by Akbari et al. [223].

Other partitioning approaches have also emerged – Cambon et al. [224] designed an approach to link the symbolic and geometric representation that permitted treatment of intricate tasks and motion planning constraints for mobile manipulator problems. More recenlty, Saoji and Rosell [225] present a task and motion planning approach which allows an easy way to interconnect both symbolic and geometric planning stages. Thakar et al. [226] developed a two-layered architecture to reduce the computation time using search trees in temporal windows and caching schemes for trees to reduce the number of calls to the motion planner. A more granular 3-stage process was pursued by Kabir et al. [227] building upon spatial constraint checking (using conservative surrogates for motion planners), instantiating symbolic conditions (for pruning infeasible assignments), and efficiently caching (and reusing) previously generated motion plans.

Coincidentally, such task- and motion-partitioning problems for mobile manipulators have also been studied in the context of the coordinated planning problem. For example, in [71] where the mobile manipulator (high dof) has to carry bulky objects like a long rod or a chair through narrow passages (large configuration spaces with significant spatial constraints over extended time-horizon). Successful pursuit of task-and motion-planning will remain crucial even as various application-deployments pursue the long-term autonomy goals.

3.1.2 Point-to-point vs Constrained Motion Planning

As a fundamental functional capability needed for the effective operation of mobile manipulators, motion planning has been pursued with 2 broad flavors: *point-to-point motion planning* to move from a starting configuration to a goal configuration (avoiding static obstacles and other primarily spatial constraints); and *constrained motion planning* addressing various spatiotemporal constraints (primarily arising from the mobile manipulator). Motion planners for high degrees of freedom systems like [57, 58, 62, 228–232] can be used for solving most motion planning problems; however, in the context of this paper, we will focus only on those planners that are designed specifically for mobile manipulators.

Historically, *point-to-point motion planning* developed the earliest and often faced the challenges of computational complexity. Hence, early exemplars often showcased decoupled mobile-base and the manipulator subsystems approaches. Doing so not only permitted modularity but potentially re-use/retasking of generic mobile-base and manipulator motion planners. However, given the dependence of the manipulator workspace on base motions, manipulators were required to be folded/homed to a standard-position. Additionally, while sequential and separate, the motion-base and manipulator motion planning were dependent – mobile-base motion depended on current (stationary) manipulator configuration while manipulator-motion planning was dependent on the current (stationary) location of the mobile base. Several approaches use the same planner [233, 234] for both mobile-base and the manipulator-planning sequentially. Similar strategies for the motion-planning of mobile base and manipulator sequentially with the additional consideration of environment uncertainty are discussed in [69, 70].

However, as noted earlier, spatiotemporal constraints arise naturally due to the dynamics within the environment and most certainly for the dynamical system engendered by the mobile-manipulator. A wide diversity of constraints can ensue based on extent of mobile-manipulator/environment coupling as well as spatial- and temporal- coupling (ie. reducibile to only spatial or only temporal).

Constraint-imposition may arise due to physics (e.g. contact) or due to heuristics (e.g. virtual fixtures) – these constraints need to be satisfied regardless the motion-planning framework. From a physics perspective, the underlying mobile manipulator constraints may be imposed at the *component-level* (kinematic actuator-rates/dynamic actuation-limits); *subsystem-level* (holonomic vs non-holonomic wheeled bases, serial/parallel/hybrid manipulators); or at the *system-level* (closed-kinematic loops due to environmental contacts, other forms of end-effector motion/force constraints). The interplay of these constraints with the environment constraints (non-holonomic motions) creates a rich fertile problem-space. The further addition of virtual constraints on both the mobile-manipulator (e.g. preferred manipulability) and environment (safety buffers) adds to the overall problem complexity. For example, the task- and motion-level planning frameworks may be viewed as a form of "artifically-constrained" motion planning within a higher dimensional space. Thus, in such a milieu, *constrained motion planning* offers a more general and certainly more contemporaneous approach but comes at the cost of increased computational complexity.

3.1.3 Optimization-based vs Sampling-based

Optimization-based and *sampling-based* offer broad categorization of motion-planning approaches deployed to address the challenges offered by: (i) the need to resolve redundancy and down-select a plan; and (ii) ever-increasing high-dimensional configuration spaces. In the context of mobile-manipulators, parametric *optimization-based methods* like in [74, 235] have been modified for the generation of constrained motions of the robot with one or more subsystems (mobile base, manipulator, gripper) moving concurrently. Additional variants [75] have encompassed aspects such as imposition of pose- and velocity-constraints such as for grasping objects as well as temporally-fluctuating imposition of constraints. Such frameworks greatly facilitate intuitive inclusion of continuity-requirements arising from the mobile manipulator dynamics/constraints. In [236], the planner simultaneously plans for the optimal location of the mobile base, as well as joint motions needed to traverse the desired end-effector path. The quadratic programming-based approach can easily incorporate additional constraints such as for wall painting, object sanding, or car washing operations using mobile manipulators. Alternately, a secondary optimization approach has been used to loosely-influence the solution constraints such as end-effector tracking for a mobile manipulator while attempting to enhance tip-over stability margins [237].

In contrast, a bulk of the growth in motion-planning for robotic manipulation has been in *sampling-based approaches* that have come to dominate the landscape. General planners like BIT* [58, 238] can be extended to the planning of holonomic and nonholonomic mobile manipulators. In these methods, the shrinking/refinement of the focus region leads to progressively better solutions when: (a) determining the initial feasible path is easy and quick, and (b) the length of the optimal path is relatively long, i.e., there is no maze-like structure in the configuration space. Pathological cases such as planning for nonholonomic mobile manipulators carrying large objects in cluttered environments do not satisfy either of these conditions and hence using these methods may not work. This is the focus of the planner presented in [71], where focus regions, hybrid sampling, and connection heuristics are used for accelerating the motion planning for mobile manipulators. Planners like TGGS [239] use separate planning-roadmaps (for base/arm) and cannot be directly used coordinated manipulator/mobile-base planning.

Other generic sampling-based methods like task-space regions, Tangent Space RRT, and Atlas-RRT [76] have been used for constrained motion-planning for mobile manipulators. The sampling-based task-constrained motion planning approach [240] enforces constraints on orientation of the object being carried are applied throughout the motion by a holonomic mobile manipulator. Random trees are grown in the in the high dimensional configuration space and samples are projected onto the appropriately constrained manifold via the mobile-manipulator Jacobian. In other work, an end-effector capability map is used together with an online sampling-based method as a desired end-effector trajectory with holonomic mobile manipulators [241].

Such Jacobian-based control can also be used to extend the trees for the nonholonomic mobile manipulator where the mobile base is constrained to move along a given path [86]. The sampling-based approach is used for unconstrained motions and relevant non-redundant inverse kinematics solutions are used for the constrained motion sections. Another sampling-based method for constrained end-effector motion planning on a point-cloud surface with a nonholonomic mobile manipulator is presented in [242]. In [68], the focus is on the planning for the mobile base so that the robot moves and picks up objects in a time-optimal manner. In [243], the requirement for the end-effector to reach a set of desired configurations requires multiple repositioning of the mobile base multiple times. First, the optimal manipulator configurations corresponding to desired end-effector poses are determined, and then successive optimal configurations are connected with minimal RRT generated paths.

Finally,it is also worth noting that several sampling-based approaches (e.g. RRT-star, A-star) can be enhanced by using physics-based measures (manipulability etc.) as additional heuristic-costs to guide the search (as discussed in the next section).

3.2 Planning Challenges Informed by Deployments

In the previous section, we noted that unique challenges emerge for specific mobile-manipulator configurations, deployed tasks and operational environments. While the arena of motion-planning in high-dimensional configuration spaces can be (and is) well studied in an abstract setting, in what follows, we will highlight the specializations pursued to address the mobile manipulation challenges. Our discussion around motion-planning deployments will be focused along 3 distinct sub-problems – Mobile base placement, Area Coverage, and Mobile Manipulator Grasping – that highlight some of the unique features and help justify the approaches

3.2.1 Redundancy Partitioning Approaches

Partitioning of base/manipulator motion capabilities within a mobile manipulator is often justified from multiple perspectives: (1) modularity (any base can now be used with any manipulator), (2) architecture-perspective (wheeled nonholonomic vs articulated serial), or (3) dynamics of manipulation (macro vs micro).

The mobile base placement (or sequence of placements) is crucial to not only ensuring feasibility of end-effector task but also its optimality. Other tasks that comprise continuous toolpaths that need to be executed on large workpieces require a sequence of mobile base placements instead of a single placement and minimization of base placements reduces the recalibration requirements. Zacharias et al. [244] used a reachability maps representation to find suitable mobile base placements so that the articulated-arm can trace Cartesian space trajectories [245] including clustered regions [246]. The work done in [247, 248] used the map to generate promising placements by sampling the workspace and improving reachability using gradient descent over the map. Other works build on computing and searching over an inverse reachability maps [249] to find suitable base locations. Reuleaux is an open-source library that also exploits inverse reachability maps to compute base placements [250]. A nearest neighbor search to obtain a set of feasible base placements together with a reachability score (for each query pose in the workspace) which can be maximized.

As in the traditional redundant manipulators cases, other end-effector criteria such as manipulability [251], end-effector stiffness [252], reachability [253], and uncertainty [243, 254] also is necessary in the mobile manipulation space [243, 252, 253].

3.2.2 Area Coverage Planning

Area coverage planning problems have been studied extensively in literature in the survey paper [255]. Area coverage is required for several robotic applications like lawn mowing [256], agricultural field plowing [257], bush trimming [258], spray painting [259], CNC machining [260], cleaning [261], etc.

When the mobile base and the manipulator move separately, coverage path planning for determining eddy currents in aeronautical parts as discussed in [262] using a zig-zag pattern can be used for a stationary mobile base. Similarly, in [263] a non-random targetted viewpoint sampling strategy for coverage planning to cover the entire area for camera-based inspection of large parts is implemented, which can be implemented for a stationary mobile base.

One of the effective methods for solving the coverage path planning problem is to formulate it as a traveling salesman problem (TSP) [264]. In [258] a bush trimming problem based on a manipulator fitted with a trimming tool at the end-effector was formulated as a TSP by using the mesh of the desired shape of the bush. Each triangle on the mesh was considered as a vertex for the TSP. Such an approach is effective only when there are not a large number of vertices. Further, they use a spline-based representation for optimization based on motion constraints for the robot such that the end-effector, i.e., the cutting tool, is constrained to go through the waypoints. In [265] a combined approach for robot placement and coverage planning for mobile manipulator, takes into account constraints like collision and stability, to determine appropriate base placements and solve the TSP for the end-effector.

The mobile base and the manipulator can move concurrently when planning for area coverage. A framework for 3D surface coverage by a redundant manipulator was implemented in [266] which can be easily extended for holonomic mobile manipulators. Here different inverse kinematic solutions for the robot are treated as individual nodes in a graph which is modeled as a generalized traveling salesman problem (GTSP). GTSP is where the nodes of a graph are subdivided into clusters, and at least one node in each cluster needs to be visited. This method can work for mobile manipulators; however, the nonholonomic nature of the mobile base can make it challenging to find feasible edges for the graph. Yang et al. [267] solved the problem of non-revisiting coverage task with minimal discontinuities for non-redundant manipulators. Leidner et al. [268] examine cleaning and wiping chores with a redundant mobile-manipulator (Rollin' Justin) where the motion plan is generated, splitting the task into a high-level planning module and a specific control for the required cleaning action with an overall objective of optimizing the traversed end-effector Cartesian path length. In this light, [269] seek an alternative approach to covering the area of a point cloud with spray disinfectant. The point cloud is first projected on a plane and a depth-first search based branch-and-bound method is pursued to cover teh extracted planar polygon extracted with a combination of zig-zag and spiral segments.

3.2.3 Mobile Manipulator Grasp Planning

Grasp planning for mobile manipulators is a challenging problem that has been dealt with in several ways in the literature. On one hand, grasping requires coordination within a very challenging high-dimensional constrained configuration space (mobile-base/manipulator/gripper). Further, grasping requires detecting object, constructing data-driven representation, determining the gripper approach-vector, and computing all the mobile manipulator's plans in the presence of uncertainty.

Many of the traditional grasp planners (designed for stationary manipulators) can be used for mobile manipulators once the mobile base has been fixed. However, an opportunity exists for stationing the mobile manipulator at an appropriate position to ensure easy grasping which several approaches have exploited. In [83], the focus is on appropriately imaging an unknown object with a mobile manipulator for its accurate reconstruction, finding appropriate planes from segmentation to successfully grasp the object. Similarly, in [270] a stereo vision algorithm is developed for the object pose estimation using point cloud data from multiple stereo vision systems. Coupled with ability to compute various grasp-metrics (e.g. via GraspIt) coupled with manipulator end-effector metrics (e.g. manipulability), this can also set the stage for secondary optimization such as for base position and end-effector approach direction [270–272].

Additionally, several of the model-based reinforcement learning approaches for robot motion and grasping have been adapted for mobile manipulation. Li et al. [84] proposed a reinforcement learning (RL) strategy for manipulation and grasping of a mobile manipulator which reduces the complexity of the visual feedback and handle varying manipulation dynamics. After several iterations of the RL and other methods, the bionic robot arm is able to reach the target position more accurately, even with unknown external perturbations. Other works [273] have also used RL for targeted grasping with active vision feedback geared towards mobile manipulators.

Dex-Net MM [85] is a deep learning framework for surface decluttering at homes where mobile manipulators with low precision can be potentially used for clearing and cleaning objects from the floor. This builds upon their previous frameworks on Dex-Net [77, 274] where physics-based models are used to determine the grasping locations on CAD models of objects. These models are learnt using deep neural networks, which are then used for grasping unknown objects from a heap of unknown objects. In [85], the Dex-Net 4.0 [275] is modified to adapt for the parameters of a mobile manipulator because, due to inherent cost and weight limits, mobile manipulators have far lower precision in sensing and control than a fixed-based robot system.

Another data-driven mobile manipulator grasping of unknown objects is presented in [276]. The goal here is to autonomously scan the environment, model the object of interest, plan and execute grasps in the presence of uncertainty in the pose of the mobile base. A single scan of the object may not reveal enough information for grasp analysis, and hence, the system autonomously builds a model of an object via multiple scans from different locations until a grasp can be performed.

All the methods mentioned above focus on manipulator motion and grasping with the mobile base stationary. However, a generic grasping pipeline is desirable which achieves arm-base-gripper coordinated grasping given the information about object pose and the operating environment. Such concurrent manipulator/mobile-base motion approaches are being explored till grasping is successful [68, 75, 86] or at least until the gripper reaches the objects (and only manipulator moves for grasping) [45, 277]

This may not be optimal as grasping can happen with the mobile base and the manipulator moving when the gripper is closing [86]. Hence, Thakar *et al.* [75] eliminate the explicit need for a stationary gripper via a strategy for mobile-base motion compensation by the manipulator arm, thereby keeping the gripper largely stationary during grasping.

3.3 Control for Mobile Manipulation

Most open-loop or feed-forward control algorithms tend to be computationally-expensive and are therefore unable to replan fast enough for ensuring timely intervention in real-time while navigating dynamic environments. Hence, feedback control approaches serve a crucial role for the robot to achieve its desired goals in a safe, accurate, and repeatable manner. Some complex planning algorithms might be deployed progressively in real-time [278], as computational resources are constantly evolving. Yet, real-time control aspects still remains the barrier for the avoidance of system failure.

As described before, in any robotic system with at least semi-autonomous capabilities, the overall software or functional architecture is broadly compartmentalized under the sense-think-act paradigm. In each of these divisions, the control algorithm or an extension of it plays a significant function. Sensing is of two types, namely proprioception, the robot's capability to identify its own states, and exteroception, its capability to identify its surroundings/environment. While exteroception is largely used in the planning and behavioral layers, proprioception appears in the robot control architecture in the form of state estimation formulations in order to eliminate uncertainties and noise introduced by the sensor suite available on the robot. Thinking involves the robot's capability to break down its functions into requirements and consequently designing its own tasks to complete those requirements. Here the role of control, generally called the upper-level controller, deals with the central problem of converting a desired path or trajectory that is computed by the planner to an acceptable and safe reference input (forces, torques, or angular rate) that an actuator can achieve. Lastly, acting involves successfully and safely performing the tasks that the robot originally set out to achieve by coordinating and operating the actuators of the robot. The problem of control may also extend further into the above-mentioned lower-level as well, where the actuators are controlled to achieve the desired angular rate references that a higher-level control computes.

The process of generating the references for the upper-level controller have been discussed in Sec. 3.2 and in this section, we will explore the control methods for mobile manipulator previously developed and deployed in the literature.

3.3.1 Criterion for Control Design

In the following, criteria for the design of control architectures are broadly categorized in context of mobile manipulator operation. This categorization follows the dominant selection in literature as pointed out by other surveys [13, 18, 19]. Additionally, Sec. 3.3.2 is introduced to capture several research contributions in niche topics within mobile manipulation that could not be categorized into the broader trends as observed in literature. This section serves as an initial starting point for developing control architecture requirements, and is not meant to exhaustive.

(A) **Path and Trajectory Control**

The motion control framework consists of a feedback algorithm that computes appropriate actuator inputs for the motion of the arm or base. Here, path control is supposed to track global spatial/geometric references that can be specified by users or a planner. Path tracking controllers have successfully been applied to robots in general [279–282] as well as in the context of mobile manipulators [283–285]. When semi-autonomous or autonomous mobile manipulator tasks are time-constrained, however, they ideally require spatio-temporal references. A higher-level motion planner generating references in the temporal space is therefore often distinguished as trajectory control [286–289]. Certain scenarios exist in which both strategies are deployed at the same time, i.e., the base being subjected to path tracking while the manipulator employs trajectory tracking (as demonstrated in [290]). It can be argued, however, that path tracking is advantageous due to its lack of unstable zero-dynamics (as present in trajectory tracking) when load carrying applications subject to unpredictable dynamic interactions are concerned, e.g. in mobile manipulation [291, 292].

(B) **Whole Body and Modular Control**

In most control approaches to mobile manipulation, base and manipulator operation are strictly separated such that at any given time only one primary control objective is active. This separation principle is then augmented by a switching layer that determines the currently pertinent control objectives. Exemplary studies that specifically address this decentralized control problem in mobile manipulators can be found in [293–297]. The advantage of such a control formulation lies in its simplicity, i.e. priorities can be separated amongst the arm and the base with individually designed different control algorithms employed for each subsystem [298].

Despite the disadvantage that unified control needs to adhere to a single control framework, it allows for the exploitation of mobile manipulation in the true sense of the term, wherein the manipulator and mobile base can be controlled at the same time. This can lead to several advantages during task achievement as discussed in Sec. 3.2 and makes the robot more dynamic in terms of its capabilities. The formulation for this type of control involves considering the onboard manipulator as an extended joint space of the mobile base, where the motion controller considers both the base and manipulator states. Here the base control becomes a lower priority task and is hence projected into the null space of the manipulator control tasks, which is now of a higher priority. As a result, base control is completed simultaneously without affecting the performance of the end-effector manipulability. Several studies have been published in the whole-body coordinated control problem of mobile manipulators where the base and the manipulator move at the same time [299–303].

(C) **Obstacle Avoidance**

In general, the problem of obstacle avoidance is largely handled at the planning level; however, since control algorithms operate much faster and largely deal with the safety of the system, several studies have included the obstacle avoidance problem (both for the base and the manipulator) at the control level. Obstacle avoidance essentially becomes one of the objectives in the robust path/trajectory control problem. Robustness plays an important factor, since a mobile manipulator can change its spatial profile drastically, large errors can cause collision with its environment. Several studies have proposed motion control algorithms for mobile manipulators that include a real-time obstacle avoidance scheme [304–307]. In most scenarios, obstacle avoidance is more efficiently enforced with the use of a unified/coordinated control algorithm that considers all the robot joints at any given time, as demonstrated in [308]. This goes back to the points discussed in Sec. 3.2, where there are several constrained obstacles such as tables, doorways, etc., that need to be considered as obstacles only for a subsystem of the robot, namely base or manipulator. The only performance metric when it comes to obstacle avoidance at a control level is the clearance margins and robustness by which the robot performs against handling said obstacles.

(D) **System Stability and Disturbance Rejection**

Stability is a large research area for mobile manipulators as it is a highly dynamic system that operates in complex environments where system failures such as tip-overs can lead to property damage or injuries. A mobile manipulator might not move at speeds that are comparable to on-road vehicles; however, since it often carries non-centric loads and goes through forceful interactions with its environment, the manipulator can dynamically disturb the base causing it to tip over. Due to the tendency of complex planning algorithms to often use low fidelity or even kinematic models during design to manage its computation loads, the references that it provides to the control level may not always lead to the safest operation of the manipulator. The purpose of these control algorithms is to act in coordination or as compensation to motion control algorithms to ensure that the system's center of gravity remains within its stable region. Several works are available in the literature studying the stability control of mobile manipulators while in operation since this is one of the biggest avenues for system failure [237, 309–314]. Another avenue of research with respect to system stability is the definition of stability margins in order to define the robustness parameters for the controller [315–317]. The control methodologies itself is explored in Sec. 3.3.2.

Disturbance rejection as a field often proves to be hand-in-glove to the stability problem when it comes to mobile manipulation. The main factors that need to be addressed in disturbance rejection are disturbances on the base due to the ground, or the manipulator due to the end-effector interactions [125, 318–320].The need for manipulators to drown out vibrations, etc., caused by the interaction between the end-effector and the work surface is a well-studied problem in robotics [321–324].

(E) **Off-road Operation**
As discussed in Sec. 2, mobile manipulators are also heavily used in outdoor applications such as search and rescue operations, construction, agriculture, etc. This raises additional complexities not only in the perception capabilities of the robot but also in the control aspects. Outside the space of mobile manipulation, navigation of ground mobile robots in off-road environments is an enormous field that consists of research spanning decades [325]. Even though mobile manipulators do not usually operate at extremely high velocities as some of the other robotics applications, the control challenges still remain significant. Researchers have studied the problem of mobile manipulation stability in unstable or deformable terrains [219, 326–328]. In general, the robustness envelopes and constraints in the indoor environments, i.e. performing constrained motion control and dynamic obstacle avoidance, have been proven to expand significantly in unstructured outdoor environments [329, 330].

3.3.2 Control Methodologies

The control methodologies employed in any autonomous robotics applications and subsequently in mobile manipulation exist within a continuum whose extremities are model-based and model-free/data-driven controls. Traditional literature from the past tends to be model-based control. However, in the last decade, the neural-network-based approach is conceived as a competitive way to control robot manipulators given the rise of computational capacity as well as significant interest in autonomy [331, 332]. Although data-driven and completely model-free control methods show a lot of promise, problems such as lack of safety guarantees, adaptability, need for large amounts of data, etc. drive researchers towards adapting a hybrid method for control that explores the best of both worlds as illustrated in [333]. In this subsection, we will explore this continuum in the literature, starting with Model-Based Control (MBC) and spanning through data-driven Model-Free Control (MFC) approaches.

In regards to MBC, fundamental issues are kinematic and dynamic modeling, the control of nonholonomic systems, the hybrid motion/force, and hybrid position/force control. There are several works one can refer to for understanding the modeling aspects of a mobile ground system, compilations of which can be found in [20, 334, 335]. In several cases, the choice of base architecture can add significant additional control challenges as well. Researches have tried to introduce suspensions to the bases of mobile manipulators to help manage the dynamics exerted on the base by the manipulator as well as increase the traversability of the robot. This, however, leads to additional necessities such as suspension control, which by itself is a vast field of research [336]. Active motion control through the use of suspensions has been explored in the field of mobile manipulators [217, 337]; however, the field is not well evolved in the research literature despite its promise. Some have tried to bypass the suspension necessities to instead use a self-balancing 2-wheel robot as

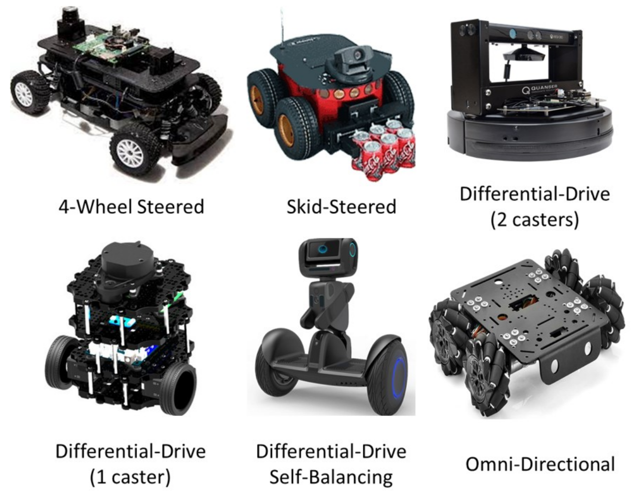

Fig. 6. Image showing several possible wheel architectures found in popular robots

the base for their mobile manipulators [338]. These robots can adjust the angle of their pitch to adjust to the terrain, which increases operational capacities significantly. There is a unique challenge with this architecture however, namely active stability control owing to their passively unstable nature. A thorough review of the advantages and state of the art in control for such a base as well as its mobile manipulator variants can be found in [339]. A preliminary look at the various architectures is presented in Fig.6.

Similar to the modeling of mobile bases, the modeling of serial link manipulators and their variants is also a well studied and researched field since the dawn of robotics [340, 341]. There are several other aspects to the analytical modeling of a manipulator that goes beyond the kinematics and dynamics itself, such as redundancy resolution, contact modeling, grasping, etc., that are also extremely important for the development of MBC algorithms. These aspects are well studied and explored, and a wealth of literature dealing with these topics exists, a compilation of which can be found in [342].

The decentralized or modular control methods discussed in Sec. 3.3.1 also extend to the modeling domain where the two subsystems can be treated separately in the control architecture. This provides some advantages since the mobile platform often has unique control properties when they are nonholonomic in nature, and it's often easier to model and control them separately for the sake of obstacle avoidance formulations, path control, etc. However, there is value in modeling the system as a whole which, despite increasing the complexities, can help exploit the value proposition of mobile manipulators completely, which is increasing the dynamic task capability of a robot. In [17], the authors derive and present the kinematics and dynamics of a differential-drive and Ackermann steered mobile platforms in great detail. Additionally, Yamamoto and Yun's body of work is often used as a popular source for extensive dynamic analysis, where modeling aspects such as dynamic task space, dynamic interaction between the manipulator and base, etc., are thoroughly explored [11, 12].

Differential-drive robots are the most common type of robotic base architectures that are used both in and outside the space of mobile manipulation. However, other platforms such as omnidirectional and skid-steered are also practically prevalent in this space, whereas the literature, on the other hand, is scarce in regards to the modeling of these systems. In [343–345], the complete kinematic and dynamic formulations are provided for an omnidirectional mobile manipulator, and a further inverse kinematics/dynamics control is developed for the trajectory tracking for the coordinated motion of the entire robot. A detailed modeling and analysis discussion was presented in [346] for skid-steered vehicles. Despite the control being a PD control (non-model-based), the work itself is interesting due to experimental validation provided for the dynamic model using a skid-steer loader. Despite the fact that wheeled mobile bases with serial chain manipulators are not the only focus of [347], a complete look into a kinematic model-based control was presented with several citations to related works. The manipulability measure is a commonly used technique in the model-based control design of manipulators. Several works now use the same measure to gauge the performance of mobile manipulators as shown in [2] whereas some studies in the literature use the manipulability measure to design their controllers. The optimization of criteria inherited from the manipulability considerations (based on an analytical model) is used to generate the whole body controls in [348]. In [308] singularities are avoided for the entire mobile manipulator by increasing the manipulability measurement. Several direct model-based active and reactive force/torque control frameworks are available in literature [349–352].

There are several model-based control methods such as optimal control and feedback linearization that do not directly use strategies such as inverse dynamics yet use an analytical model as an assumption for system behavior in the control design phase. Optimal control has proven to be effective in several scenarios as shown by [353–356] where variants of Model Predictive Control (MPC) was successfully applied in navigation control for mobile manipulators. Further, given that the dynamics are known, feedback linearization techniques for mobile manipulators have attracted research interest in recent years. Input-output feedback linearization was applied to control the navigation of the mobile base such that the best manipulator position can be achieved at the preferred configurations (measured by its manipulability) in [302]. Similarly, in [11, 357, 358], decoupled control was performed using feedback linearization methods where force control of the end effector was achieved while simultaneously compensating for the dynamic interactions between the base and the arm.

Compilations of the latest literature in classical model identification methods[359] and modern robot learning methods [360] often indicate a trend towards the deployment of data-driven methods to learn an input-output relationship for the robot. Additionally, control of mobile manipulators with uncertainties is essential in many practical applications, especially for the case when the force of the end-effector needs to be considered. In the space of mobile manipulation, the method that seems to be prevalent in literature for the handling of model or parameter uncertainties is robust and adaptive control techniques.

One such primary control method that has been extensively used in the field of mobile manipulators is Variable Structure Control/Sliding Mode Control (VSC/SMC), owing to its desirable tolerance to some degree of parameter uncertainty [361–363]. In such methodologies, a discontinuous control law is employed to guide the system to a switching surface wherein once the system is on the switching surface, the control law guarantees that the dynamics are insensitive to parameter variations. Further complex robust control techniques such as backstepping control [364] and its variants in combination with SMC[365], etc. have been deployed. In [91], a nonlinear robust control technique was presented based on compensation for uncertainty which was predicted/estimated using a disturbance observer. It is also noteworthy that some have designed robust control techniques based on dynamic compensation or torque compensation to eliminate the disturbance caused by the coupling of the base and manipulator [366, 367].

Adaptive control methods can effectively cope with parameter errors as well as modeling errors by adapting controller gains. The feedback from the plant is designed in such a way that the end behavior is identical to the ideal system described by the analytical model. Several studies have used adaptive control directly for common control problems such as trajectory tracking, force control, etc [104, 284, 368–370]. A variant of adaptive control is robust adaptive control wherein further error feedback is added for robustness which has also been explored in literature [124, 371–373]. Further advanced techniques can be combined to add robustness to adaptive control as shown in [374] where sliding mode control was used for disturbance suppression while adaptive control took care of uncertainties. An adaptive force control technique was presented in [375] where robustness was added to attenuate disturbances.

In accordance with the discussion of the control methodologies being a continuum, a lot of model-free methods have risen in the recent past. An explanation of the fundamentals of these methodologies and references for the latest literature in the domain of static manipulators can be found in [331, 376]. Methods such as reinforcement learning (RL) bypass the need for model-based design by learning a feedback control law based on data and have already been used extensively in the mobile manipulation paradigm. Rule-based approaches such as fuzzy logic controllers can also can be categorized as MFCs [377–379]. A pick-n-place motion tracking operation was controlled using the end-to-end deep RL technique in [97], wherein the base was controlled based on a controller that was learned using the manipulator end-effector task space data. In [380], a whole-body control algorithm was learned using RL, and the visual sensor information was used as the training data for the same. Similarly, a whole-body control algorithm based on RL was proposed in [381] in which the training was based on LiDAR scans of the robot. A hierarchical controller where the lower level joint space control alone is designed using RL was presented in [382]. On a different note, in [383], RL was used to learn the kinematic feasibility and manipulability of a mobile manipulator. The same is then used for dynamic motion generation for the robot to track the task space references. Apart from RL, neural networks and their variants (recurrent, etc.) have also been used in the literature to map sensor data/output to a feasible input using a trained controller [384–387]. The problem of uneven terrain handling is also solved using a learning-based control algorithm in [388]. A similar application: robot parking amongst uncertainty and cloudy sensor data, has been solved using learning methods in [389]. A neural net-based tip-over avoidance controller that both detects and provides real-time mitigation control inputs to avoid tip-overs was proposed in [237]. Apart from directly just learning data-driven controllers, neural nets have also been deployed to solve nonlinear optimization problems. A robust zeroing neural network was proposed in [283] that deployed a successful robotic manipulator path tracking example in a noise polluted environment to show its versatility.

A deduction can be made that MFC approaches are undeniably effective in handling the problems of mobile manipulation. However, the application scenarios and literature still raises questions about these methods in terms of repeatability, safety, guarantees, adaptability, etc. There have been hybrid methods in the literature that aim to combine the best from MBC, and MFC approaches to truly expand the capabilities of mobile manipulators and other systems in general. Several published works in the mobile manipulator space focus on hybrid methods integrating system dynamics-based control for robustness and learning-based methods for adaptability[390]. Sliding mode control combined with intelligent methods has been explored in [391, 392] where a robust controller is designed using the system dynamics in order to bring them to a sliding surface post which a learned proportional control acts as compensation for adaptive operation. Alternatively, a combination of fuzzy control and neural networks have been presented in [393, 394] wherein the fuzzy control takes care of generating control for navigation while the neural net acts as a robustness compensator. In a manner of perfect collision of both worlds, a model-based control that performs inverse dynamics for control is augmented using a neural net for robustness in [395]. Lastly, in [396], a neural network was trained to provide feedforward torque which was then layered with a fuzzy-based feedback loop. Additionally, the weights of the neural network were continually updated using an Extended Kalman Filter (EKF) in real-time that estimates the best weights based on the system output measurement.

For quick reference, a graphical representation of the literature existing in the continuum discussed in this section is presented in Fig. 7

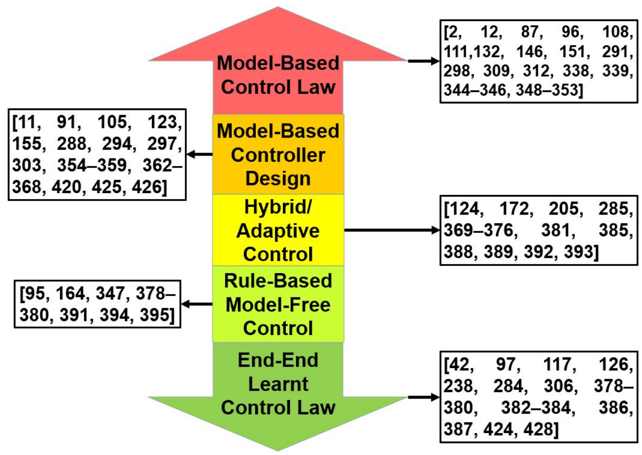

Fig. 7. The continuum in literature in regards to control methodology ranging from Model-Based to End-End data-driven control.

3.4 Human and Mobile Manipulator Collaboration

Human-robot collaboration is an important aspect of mobile manipulators used in a variety of applications. In fact most applications require some level of human control [142, 143, 156, 397], and interaction of the robots with humans [142, 398–400] regardless of the autonomy level applied. Manual control of mobile manipulators can often be very challenging for humans since it is challenging to perceive the robot's surroundings perfectly as the base or arm moves. Furthermore, the relationship between joint angles of a high DOF robotic arm and its resultant pose in Cartesian space is extremely non-intuitive for human operators. There needs to be a good balance between the level of autonomous decision making and human oversight [401] so that workload of the human operator is minimized while improving robot performance. Moreover, robots often need to have physical interactions with humans in the workplace while assisting them or collaborating on a task. This requires robots to have decision making capabilities about how to interact with humans safely and efficiently.

There are many works focusing on the different human-robot interfaces for controlling a mobile manipulator. Work described in [402] presents a remote manipulation method using operator gesture which can be employed by a non-professional operator. Their proposed human-robot interface is able to track the movements of the operator's hand with high accuracy. A system reported in [143] uses a 3-DOF interface like a sip-puff or joy-stick to command end-effector for performing pick and place operations, to be used by mobility-impaired people. Work described in [401] demonstrates a sufficient level of automation with AI features, where the remote operator can use an interface on the computer to navigate and perform object retrieval and placement, disinfecting surfaces, etc. Voice commands have been explored to task an autonomous mobile manipulator to do simple domestic tasks [131], [140], [141].

In the case of the teleoperation of a mobile manipulator from a remote location, the human operator often feels a disconnect from the actual location where the robot is operating. To ensure transparency in teleoperation, work presented in [403] demonstrates an augmented reality-based system to give the operator the feel of the operation site of the robot, where they consider senses of sight, touch, and hearing. Another intuitive way is to integrate Virtual Reality (VR) interfaces with the control system of a mobile manipulator as demonstrated in [404].

Delivering an object to a human is a useful general-purpose capability for an assistive mobile manipulator to have. Work reported in [399] describes a service robot where control issues are addressed for delivering and handing over objects to a human. Work described in [142] presents a user study for object delivery to motor-impaired patients autonomously. They compare performance between having the object to the user (direct delivery) and placing the object on a nearby table (indirect delivery). They conclude that indirect delivery is more robust and reliable with high user satisfaction.

Assistive tasks often require tactile and pressure sensing capability. Work described in [405] uses pressure-sensitive robot skin for physical human-robot interaction for performing assistive tasks. Work reported on [406] exploits the multi-modal tactile information of the robot skin. The paper presents the mechatronic design of their Tactile Omnidirectional Robot Manipulator (TOMM), which has its arms and hands covered with robot skin.

When a mobile manipulator operates in an environment with humans, it is important to ensure the safety of the people. The autonomous mobile manipulator in [407] uses heat-map-based social density monitoring for selective cleaning while maintaining social distancing with surrounding humans. Tele-nursing robots like TRINA [156] require safety in close proximity humans. This can be especially useful in case of quarantine situation or when a hospital needs a sudden expansion of caregiving capacity.

Work reported in [408] describes Code3, which is a system for user-friendly, rapid programming of mobile manipulators. Work presented in [409] described a human-robot interface based on task-level programming and kinesthetic teaching in order to simply programming specifically for industrial tasks. The interface was assessed by people with varying robotics experience, and the goal is to make it available for production floor operators in industrial settings.

Collaborative tasks with humans can be especially challenging since the robot requires sufficient adaptivity and safety measures. Work reported in [410] deals with active cooperative tasks between a mobile manipulator and a human, like carrying a long object together. They demonstrate an intention recognition capability in the robot based on the search for spectral patterns in the force signal measured at the arm gripper. Work described in [398] presents a robotic architecture for human-robot interaction with a human-aware manipulation planner for safety and a supervision system dedicated to collaborative task achievement. Work reported in [397] presents a control strategy for intuitive physical human-robot collaboration with mobile manipulators equipped with an omnidirectional base.

4 Future Challenges

The mobile manipulator can be used for a wide variety of tasks since the environment where they need to work is designed for humans, and the structures of mobile manipulators resemble human anatomy, i.e., they have a robotic arm on a mobile platform. However, in order to make them more useful, mobile manipulators need to perform tasks that are challenging for humans. With this in mind, here are some of the potential future challenging problems that one can work on.

High-speed Manipulation and Grasping: Grasping or manipulating an object while the mobile base moves at high speed can have several benefits. It can optimize pick-up and transportation tasks. However, it is a challenging task due to the precise coordination between the arm and the mobile base required. For example, grasping an object while moving requires high-speed perception, precise control, and appropriate motion planning of the mobile manipulator. Work has been done on grasping moving objects with a stationary manipulator [411], but the problem of grasping or moving objects when the mobile base has to move at high speeds is further challenging due to the coordinated motions of the mobile base and the manipulator that is required. Further, uncertainty in the pose of the object can add further complications to the problem. Hence, it is necessary to study this problem in detail by integrating the perception, planning, and control of the robot. Also, demonstrating this where the mobile base moves at high speeds is also a future direction in this area.

Navigating mobile base with manipulator-based sensing: Another area of research that can be explored is to use sensors attached to a manipulator to navigate the mobile manipulator. For example, in tight spaces where the uncertainty in the pose of the base results in a high probability of collision, a camera with vision sensors can dynamically move and image parts of the robot close to the obstacle. If this is done with the mobile base and the manipulator moving together, where the manipulator moves to configurations that image such situations, it can result in safe navigation of the robot. Furthermore, if there are tactile sensors and impedance control on the manipulator, it can use this to get a sense of how far obstacles are for mobile base motions, where the vision system may not be reliable.

Mobile Manipulator Design: Mobile manipulator design plays an important role in the accuracy of execution of the computed trajectories. A more dynamically stable manipulator will be accurate in performing high-speed tasks. At present, a mobile manipulator is constructed by integrating a commercially available base and a manipulator. The integration requires designing a structure on the base to support the manipulator, controller, and other equipment. Lack of design principles will often lead to an unstable system and a higher center of gravity of the mobile manipulator. Careful consideration of the weights and balance of equipment on the mobile manipulator can be given to improve the accuracy. Research work can be done in this area to study how the construction of the mobile base influences the trajectory execution. The structured design of the robot will also generate a known dynamic model that can be used during planning.

Multi-Arm Mobile Manipulation: The simplest version of a mobile manipulator, i.e., with one arm planning, is well studied. But a mobile manipulator with one arm is not always the best solution for an application. A few applications such as machine tending, assembly, hospital tasks, and more are possible or done more efficiently with a mobile manipulator with two or more arms. Two or more arms make the planning problem different and complex. For example, the task planning, the number of agents increases with the number of arms, and these agents need to communicate for efficient task execution. In the case of motion planning, multiple arms add dynamic obstacles for each manipulator, and the motion planning problem has avoided collisions with other manipulators in their path. Also, there are applications that require multiple arms to move in a synchronous manner. All these applications and challenges show that a lot of research is still to be done for multi-arm mobile manipulation.

Analytical Study of Collision and Interaction Behaviors: Planning algorithms and navigation strategies have almost entirely aimed at avoiding collisions, with the obstacles and workspace boundaries serving to impose constraints on robot paths. In the past, robots' structural and internal components were expensive, fragile, and in general not considered dispensable, which clearly motivated the urge for collision avoidance. Today, however, new methods for manufacturing have enabled the development of a different class of robots that can either withstand collisions or be considered dispensable when they do not always survive them. There has even been evidence that robotic missions can benefit from contact with the environment. Yet efforts to understand, implement, and exploit such behaviors are still in their infancy. Early work demonstrates the potential for physical robot-environment interaction to contribute to new strategies for motion planning. Mobile manipulators offer more room for the designer to make them robust to collisions, add shielding, and even employ mechanisms to exploit boundary interactions. Mathematical models that capture impact behavior and planners that intentionally incorporate these behaviors are currently under-developed.

Transportation and Manipulation Deformable Objects: Mobile robots can come in handy for transportation or manipulation of deformable objects. Industrial applications often require transporting flexible materials from one factory station to the other. The materials need to be handled by a collaborative effort between multiple human operators leading to a loss of valuable human labor. Advances in the planning of synchronized trajectories for multiple mobile manipulators to carry and transport flexible materials can be made. The materials are also required to be manipulated and stored. For instance, composite industries require transportation and manipulation of large flexible composite sheets from the material station to the mold on which they are formed. Planning synchronous trajectories for multiple mobile robots poses algorithmic challenges that can be solved in future research.

Energy Efficient Mobile Manipulator: Mobile manipulators, when deployed, need to be energy efficient to be economically feasible. If the mobile manipulator needs to charge while performing a task, it slows it down and adds downtime. Technologies like fast charging and batteries with higher charge density are necessary for that. Along with these, efficient task and motion planning can also be very useful. In the case of multiple mobile manipulators, the tasks should be planned such that the overall energy utilization is low and the energy usage is equally distributed between multiple mobile manipulators. Motion planning can be done in a way that the mobile base uses the least amount of energy, and the manipulator does not need to perform inefficient manipulations. This area of research will be very useful for industries aiming to adopt mobile manipulators in a sustainable and economically feasible manner. So it should be pursued by researchers.

Safe operation in the presence of humans: We envision mobile manipulators operating alongside humans within an environment in the future. In order to achieve that, absolute safety needs to be guaranteed. While there have been lots of works on human-safe industrial robotic manipulators [412–414] and automatic guided vehicles (AGVs) or mobile robots [415–417], there are not as many works for mobile manipulators. A mobile manipulator comes with its own challenges for the integration of robotic arm(s) onto a mobile base. [418] describes safety standards specifically for mobile manipulators in modern manufacturing and discusses the need for a new class of test artifacts for mobile manipulators in collaborative environments. Ensuring safety requires development on three major fronts. Firstly, we need superior and reliable sensing capability, which has zero to little uncertainty in perceiving its environment dynamically. Secondly, the system needs to find, plan and execute appropriate corrective actions based on the sensor feeds. Lastly, in case of an unavoidable collision, the system needs to minimize human injury. Reliability in all these features will ensure safety for the surrounding humans, which would escalate the real-world deployment of mobile manipulators in the future.

Hybrid Control Methods: Mobile manipulator systems often get very complex, and their complexity is only going to increase owing to the rapid deployment of robots for several advanced tasks in industry settings. As the complexity of the systems increase, often the modeling of these systems using first principles become extremely difficult, rendering model-based control unideal. There has been a steady rise in the deployment of data-driven control methodologies, as many modern industrial processes produce huge amounts of process data containing all the valuable state information about its own dynamics and state-flows. Designing controllers or estimators directly using these data, online and/or off-line, is extremely appealing especially given the lack of accurate process models. However, in applications such as mobile manipulators that operate amongst humans, safety is of great concern, hence requiring rigorous verification and safety guarantees before deployment. Here is where model-based control holds a greater advantage due to the fact they are verifiable, repeatable, and explainable. It is clear that both these control methodologies hold significant strengths that make a case for each; however, we envision hybrid methods that combine the best of both worlds can greatly benefit the automation of mobile manipulators. Although explainable Artificial Intelligence (AI) and hybrid control strategies are popular research topics in robotics, there are significant gaps in research on this topic, particular to mobile manipulators, and hence research in hybrid control theory applied to mobile manipulators is the necessary future direction.

Human and mobile manipulator collaboration: There are many open challenges towards next-generation human-robot collaboration with mobile manipulators. We have more works on human-robot interfaces (HRI) for robotic manipulators and AGVs separately than we have for mobile manipulators. We need improved communication modalities to ensure natural communication between robots and humans. The most common kinds of communications would be humans providing instructions to the robot and the robot relaying new information to humans. Voice-based or natural language-based communication can be extremely natural for humans, but gestures, augmented reality (AR) or virtual reality (VR) systems, or even joystick and computer keyboard-mouse and screen displays can also provide useful functionalities for HRI. Another aspect includes mobile manipulators performing physically collaborative tasks with humans. Most of the features we mentioned for safe operation in the presence of humans will be useful for such collaborative tasks.

5 Conclusions

Research interest in integrating the mobility of mobile robots and the manipulability of manipulators to provide enlarged workspaces and adaptability in various operations has had a significant presence in robotics in the past few decades. Despite its theoretical merit, the implementation of such systems in actual applications has largely been limited due to significant challenges related to online planning and control. However, in recent times, the triple convergence of developments in miniaturized computing, sensing, and advanced algorithms have provided a lot of capabilities that enable robots to graduate from mere automated systems to autonomous ones. These capabilities have now brought about a renewed interest in mobile manipulators, which are being considered in new applications at a rapid rate. Autonomous deployment for mobile manipulators is emerging as new fields of research fostering advances in industry 4.0. In recent times, research in all aspects of mobile manipulators, from design optimization and architecture to perception and decision-making, has been on the rise. Our focus has been limited to the decision-making methodologies of wheeled mobile manipulators in this paper. Several research challenges and future directions are outlined in this study that needs to be addressed and pursued in order to further expand the applicability of mobile manipulators in challenging applications. The scope of necessary research is not only limited to particularly robotics but, as outlined in this study, also expands to several fundamental theoretical areas that need advances. Further advances in these areas will enable not only mobile manipulators to be more effectively deployed in existing applications but also enable new applications.

References

[1] Christensen, H. I., Amato, N., Yanco, H., Mataric, M., Choset, H., Drobnis, A. W., Goldberg, K., Grizzle, J., Hager, G., Hollerbach, J., Hutchinson, S., Krovi, V., Lee, D., Smart, B., Trinkle, J., and Sukhatme, G., 2021. "A roadmap for us robotics - from internet to robotics 2020 edition". *Found. Trends Robotics,* **8**, pp. 307–424.

[2] Bayle, B., Fourquet, J.-Y., and Renaud, M., 2001. "Manipulability analysis for mobile manipulators". In Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation (Cat. No.01CH37164), Vol. 2, pp. 1251–1256 vol.2.

[3] De Luca, A., Oriolo, G., and Giordano, P. R., 2007. "Image-based visual servoing schemes for nonholonomic mobile manipulators". *Robotica,* **25**(2), p. 131–145.

[4] Fruchard, M., Morin, P., and Samson, C., 2006. "A framework for the control of nonholonomic mobile manipulators". *The International Journal of Robotics Research,* **25**(8), pp. 745–780.

[5] Park, J., and Khatib, O., 2006. "A haptic teleoperation approach based on contact force control". *The International Journal of Robotics Research,* **25**(5-6), pp. 575–591.

[6] Seraji, H., 1998. "A unified approach to motion control of mobile manipulators". *The International Journal of Robotics Research,* **17**(2), pp. 107–118.

[7] Tang, C. P., Bhatt, R., Abou-Samah, M., and Krovi, V., 2006. "Screw-theoretic analysis framework for cooperative payload transport by mobile manipulator collectives". *IEEE/ASME Transactions on Mechatronics,* **11**(2), pp. 169–178.

[8] Stentz, A., Bares, J., Singh, S., and Rowe, P., 1998. "A robotic excavator for autonomous truck loading". In Proceedings. 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems. Innovations in Theory, Practice and Applications (Cat. No.98CH36190), Vol. 3, pp. 1885–1893 vol.3.

[9] Gardner, J. F., and Velinsky, S. A., 2000. "Kinematics of mobile manipulators and implications for design". *Journal of Robotic Systems,* **17**(6), pp. 309–320.

[10] Colbaugh, R., Trabatti, M., and Glass, K., 1999. "Redundant nonholonomic mechanical systems: characterization and control". *Robotica,* **17**(2), p. 203–217.

[11] Yamamoto, Y., and Yun, X., 1996. "Effect of the dynamic interaction on coordinated control of mobile manipulators". *IEEE Trans. Robot. Autom.,* **12**(5), pp. 816–824.

[12] Yamamoto, Y., and Yun, X., 1999. "Unified analysis on mobility and manipulability of mobile manipulators". *Proc. - IEEE Int. Conf. Robot. Autom.,* **2**(May), pp. 1200–1206.

[13] Bostelman, R., Hong, T., and Marvel, J., 2016. "Survey of research for performance measurement of mobile manipulators". *Journal of Research of the National Institute of Standards and Technology,* **121**, p. 342.

[14] Song, Z.-s., Yi, J.-q., and Zhao, D.-b., 2003. "Survey of the control for mobile manipulators". *Robot,* **25**(5), pp. 465–480.
[15] Youakim, D., and Ridao, P., 2018. "Motion planning survey for autonomous mobile manipulators underwater manipulator case study". *Robotics and Autonomous Systems,* **107**, pp. 20–44.
[16] Khamseh, H. B., Janabi-Sharifi, F., and Abdessameud, A., 2018. "Aerial manipulation—a literature survey". *Robotics and Autonomous Systems,* **107**, pp. 221–235.
[17] Li, Z., 2017. *Fundamentals in Modeling and Control of Mobile Manipulators*. Taylor and Francis Group.
[18] Sereinig, M., Werth, W., and Faller, L. M., 2020. "A review of the challenges in mobile manipulation: systems design and RoboCup challenges: Recent developments with a special focus on the RoboCup". *Elektrotechnik und Informationstechnik,* **137**(6), pp. 297–308.
[19] Yang, M., Yang, E., Zante, R. C., Post, M., and Liu, X., 2019. "Collaborative mobile industrial manipulator: A review of system architecture and applications". *ICAC 2019 - 2019 25th IEEE Int. Conf. Autom. Comput.*(September), pp. 5–7.
[20] Campion, G., and Chung, W., 2008. "Wheeled Robots". *Springer Handbook of Robotics*, pp. 391–410.
[21] Alamdari, A., and Krovi, V., 2016. "Static balancing of articulated wheeled vehicles by parallelogram- and spring-based compensation". *Dynamic Balancing of Mechanisms and Synthesizing of Parallel Robots*, p. 513–527.
[22] Alamdari, A., and Krovi, V. N., 2016. "Static balancing of highly reconfigurable articulated wheeled vehicles for power consumption reduction of actuators". *International Journal of Mechanisms and Robotic Systems,* **3**(1), p. 15.
[23] Alamdari, A., Zhou, X., and Krovi, V. N., 2013. "Kinematic modeling, analysis and control of highly reconfigurable articulated wheeled vehicles". *Volume 6A: 37th Mechanisms and Robotics Conference*.
[24] Fu, Q., Zhou, X., and Krovi, V., 2014. "The reconfigurable omnidirectional articulated mobile robot (roamer)". *Experimental Robotics*, p. 871–882.
[25] , 2002. Optimal Configuration Selection for a Cooperating System of Mobile Manipulators, Vol. Volume 5: 27th Biennial Mechanisms and Robotics Conference of *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*.
[26] Tang, C. P., 2004. Manipulability-based analysis of cooperative payload transport by robot collectives.
[27] Yoshikawa, T., 2003. *Foundations of Robotics: Analysis and Control*. The MIT Press, 01.
[28] Lynch, K. M., and Park, F. C., 2019. *Modern robotics: Mechanics, planning, and control*. Cambridge University Press.
[29] Murray, R. M., Li, Z., and Sastry, S. S., 1993. *A mathematical introduction to robotic manipulation*. Crc Press.
[30] Spong, M. W., Hutchinson, S., and Vidyasagar, M., 2020. *Robot modeling and control*. John Wiley and Sons.
[31] Siciliano, B., and Khatib, O., 2016. *Springer Handbook of robotics*. Springer.
[32] Desouza, G., and Kak, A., 2002. "Vision for mobile robot navigation: a survey". *IEEE Transactions on Pattern Analysis and Machine Intelligence,* **24**(2), pp. 237–267.
[33] Bavle, H., Sanchez-Lopez, J. L., Schmidt, E. F., and Voos, H., 2021. From slam to situational awareness: Challenges and survey.
[34] Lin, H., 2020. "Robotic manipulation based on 3d vision: A survey". In Proceedings of the 2020 International Conference on Pattern Recognition and Intelligent Systems, PRIS 2020, Association for Computing Machinery.
[35] Martinez-Martin, E., and del Pobil, A. P., 2019. "Vision for robust robot manipulation". *Sensors,* **19**(7).
[36] Bai, Q., Li, S., Yang, J., Song, Q., Li, Z., and Zhang, X., 2020. "Object detection recognition and robot grasping based on machine learning: A survey". *IEEE Access,* **8**, pp. 181855–181879.
[37] Rasouli, A., 2020. Deep learning for vision-based prediction: A survey.
[38] Kragic, D., and Christensen, H. I., 2002. "Survey on visual servoing for manipulation".
[39] Ribeiro, E. G., de Queiroz Mendes, R., and Grassi, V., 2021. "Real-time deep learning approach to visual servo control and grasp detection for autonomous robotic manipulation". *Robotics and Autonomous Systems,* **139**, May, p. 103757.
[40] Belmonte, Á., Ramón, J. L., Pomares, J., Garcia, G. J., and Jara, C. A., 2019. "Optimal image-based guidance of mobile manipulators using direct visual servoing". *Electronics,* **8**(4).
[41] Bonci, A., Cen Cheng, P. D., Indri, M., Nabissi, G., and Sibona, F., 2021. "Human-robot perception in industrial environments: A survey". *Sensors,* **21**(5).
[42] Tsai, C.-Y., Chou, Y.-S., Wong, C.-C., Lai, Y.-C., and Huang, C.-C., 2020. "Visually guided picking control of an omnidirectional mobile manipulator based on end-to-end multi-task imitation learning". *IEEE Access,* **8**, pp. 1882–1891.
[43] Arora, P., and Papachristos, C., 2020. "Mobile manipulator robot visual servoing and guidance for dynamic target grasping". In Advances in Visual Computing, G. Bebis, Z. Yin, E. Kim, J. Bender, K. Subr, B. C. Kwon, J. Zhao, D. Kalkofen, and G. Baciu, eds., Springer International Publishing, pp. 223–235.
[44] Zhao, W., and Wang, H., 2020. "Adaptive image-based visual servoing of mobile manipulator with an uncalibrated fixed camera". In 2020 IEEE International Conference on Real-time Computing and Robotics (RCAR), pp. 440–445.
[45] Jiao, J., Ye, S., Cao, Z., Gu, N., Liu, X., and Tan, M., 2012. "Embedded vision-based autonomous move-

to-grasp approach for a mobile manipulator". *International Journal of Advanced Robotic Systems,* **9**(6), p. 257.

[46] Zapata-Impata, B. S., Shah, V., Singh, H., and Platt, R., 2018. "Autotrans: An autonomous open world transportation system". *arXiv preprint arXiv:1810.03400*.

[47] Nishida, T., Takemura, Y., Fuchikawa, Y., Kurogi, S., Ito, S., Obata, M., Hiratsuka, N., Miyagawa, H., Watanabe, Y., Koga, F., et al., 2006. "Development of outdoor service robots". In 2006 SICE-ICASE International Joint Conference, IEEE, pp. 2052–2057.

[48] Dömel, A., Kriegel, S., Kaßecker, M., Brucker, M., Bodenmüller, T., and Suppa, M., 2017. "Toward fully autonomous mobile manipulation for industrial environments". *International Journal of Advanced Robotic Systems,* **14**(4), p. 1729881417718588.

[49] Annem, V., Rajendran, P., Thakar, S., and Gupta, S. K., 2019. "Towards remote teleoperation of a semi-autonomous mobile manipulator system in machine tending tasks". In ASME 2019 14th International Manufacturing Science and Engineering Conference, American Society of Mechanical Engineers Digital Collection.

[50] Wise, M., Ferguson, M., King, D., Diehr, E., and Dymesich, D., 2016. "Fetch and freight: Standard platforms for service robot applications". In Workshop on autonomous mobile service robots.

[51] Shepherd, S., and Buchstab, A., 2014. "Kuka robots on-site". In *Robotic Fabrication in Architecture, Art and Design 2014*. Springer, pp. 373–380.

[52] Taipalus, T., and Kosuge, K., 2005. "Development of service robot for fetching objects in home environment". In 2005 International Symposium on Computational Intelligence in Robotics and Automation, IEEE, pp. 451–456.

[53] Jain, A., and Kemp, C. C., 2010. "El-e: an assistive mobile manipulator that autonomously fetches objects from flat surfaces". *Autonomous Robots,* **28**(1), p. 45.

[54] Fan, Z., King, C.-H., Darb, H., and Kemp, C. C., 2010. "Dusty: A teleoperated assistive mobile manipulator that retrieves objects from the floor". Georgia Institute of Technology.

[55] Jian-Jun, Z., Ru-Qing, Y., Wei-Jun, Z., Xin-Hua, W., and Jun, Q., 2007. "Research on semi-automatic bomb fetching for an eod robot". *International Journal of Advanced Robotic Systems,* **4**(2), p. 27.

[56] Cakmak, M., Srinivasa, S. S., Lee, M. K., Forlizzi, J., and Kiesler, S., 2011. "Human preferences for robot-human hand-over configurations". In 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, pp. 1986–1993.

[57] Kuffner, J. J., and LaValle, S. M., 2000. "Rrt-connect: An efficient approach to single-query path planning". In Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No. 00CH37065), Vol. 2, IEEE, pp. 995–1001.

[58] Gammell, J. D., Barfoot, T. D., and Srinivasa, S. S., 2020. "Batch informed trees (bit*): Informed asymptotically optimal anytime search". *The International Journal of Robotics Research,* **39**(5), pp. 543–567.

[59] Rickert, M., Brock, O., and Knoll, A., 2008. "Balancing exploration and exploitation in motion planning". In 2008 IEEE International Conference on Robotics and Automation, IEEE, pp. 2812–2817.

[60] Rajendran, P., Thakar, S., Kabir, A. M., Shah, B. C., and Gupta, S. K., 2019. "Context-dependent search for generating paths for redundant manipulators in cluttered environments". In 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, pp. 5573–5579.

[61] Kabir, A. M., Shah, B. C., and Gupta, S. K., 2018. "Trajectory planning for manipulators operating in confined workspaces". In 2018 IEEE 14th International Conference on Automation Science and Engineering (CASE), IEEE, pp. 84–91.

[62] Gammell, J. D., Srinivasa, S. S., and Barfoot, T. D., 2014. "Informed rrt*: Optimal sampling-based path planning focused via direct sampling of an admissible ellipsoidal heuristic". In 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, pp. 2997–3004.

[63] Ratliff, N., Zucker, M., Bagnell, J. A., and Srinivasa, S., 2009. "Chomp: Gradient optimization techniques for efficient motion planning". In 2009 IEEE International Conference on Robotics and Automation, IEEE, pp. 489–494.

[64] Kalakrishnan, M., Chitta, S., Theodorou, E., Pastor, P., and Schaal, S., 2011. "Stomp: Stochastic trajectory optimization for motion planning". In 2011 IEEE international conference on robotics and automation, IEEE, pp. 4569–4574.

[65] Pivtoraiko, M., Knepper, R. A., and Kelly, A., 2009. "Differentially constrained mobile robot motion planning in state lattices". *Journal of Field Robotics,* **26**(3), pp. 308–333.

[66] Laumond, J.-P., Jacobs, P. E., Taix, M., and Murray, R. M., 1994. "A motion planner for nonholonomic mobile robots". *IEEE Transactions on robotics and automation,* **10**(5), pp. 577–593.

[67] Simba, K. R., Uchiyama, N., and Sano, S., 2016. "Real-time smooth trajectory generation for nonholonomic mobile robots using bézier curves". *Robotics and Computer-Integrated Manufacturing,* **41**, pp. 31–42.

[68] Thakar, S., Fang, L., Shah, B., and Gupta, S., 2018. "Towards time-optimal trajectory planning for pick-and-transport operation with a mobile manipulator". In 2018 IEEE 14th International Conference on Automation Science and Engineering (CASE), IEEE, pp. 981–987.

[69] Pilania, V., and Gupta, K., 2018. "Mobile manipulator planning under uncertainty in unknown environments". *The International Journal of Robotics Research,* **37**(2-3), pp. 316–339.

[70] Pilania, V., and Gupta, K., 2015. "A hierarchical and adaptive mobile manipulator planner with base pose uncertainty". *Autonomous Robots,* **39**(1), pp. 65–85.

[71] Thakar, S., Rajendran, P., Kim, H., Kabir, A. M., and Gupta, S. K., 2020. "Accelerating bi-directional sampling-based search for motion planning of non-holonomic mobile manipulators". In IEEE/RSJ International Conference on Intelligent Robots and System (IROS).

[72] Oriolo, G., and Mongillo, C., 2005. "Motion planning for mobile manipulators along given end-effector paths". In Proceedings of the 2005 IEEE International Conference on Robotics and Automation, IEEE, pp. 2154–2160.

[73] Mohri, A., Furuno, S., and Yamamoto, M., 2001. "Trajectory planning of mobile manipulator with end-effector's specified path". In Proceedings 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems. Expanding the Societal Role of Robotics in the the Next Millennium (Cat. No. 01CH37180), Vol. 4, IEEE, pp. 2264–2269.

[74] Kabir, A. M., Kanyuck, A., Malhan, R. K., Shembekar, A. V., Thakar, S., Shah, B. C., and Gupta, S. K., 2019. "Generation of synchronized configuration space trajectories of multi-robot systems". In 2019 International Conference on Robotics and Automation (ICRA), IEEE, pp. 8683–8690.

[75] Thakar, S., Rajendran, P., Annem, V., Kabir, A., and Gupta, S., 2019. "Accounting for part pose estimation uncertainties during trajectory generation for part pick-up using mobile manipulators". In 2019 International Conference on Robotics and Automation (ICRA), IEEE, pp. 1329–1336.

[76] Kingston, Z., Moll, M., and Kavraki, L. E., 2018. "Sampling-based methods for motion planning with constraints". *Annual review of control, robotics, and autonomous systems,* **1**, pp. 159–185.

[77] Mahler, J., Liang, J., Niyaz, S., Laskey, M., Doan, R., Liu, X., Ojea, J. A., and Goldberg, K., 2017. "Dex-net 2.0: Deep learning to plan robust grasps with synthetic point clouds and analytic grasp metrics". *arXiv preprint arXiv:1703.09312*.

[78] Mahler, J., Pokorny, F. T., Hou, B., Roderick, M., Laskey, M., Aubry, M., Kohlhoff, K., Kröger, T., Kuffner, J., and Goldberg, K., 2016. "Dex-net 1.0: A cloud-based network of 3d objects for robust grasp planning using a multi-armed bandit model with correlated rewards". In 2016 IEEE international conference on robotics and automation (ICRA), IEEE, pp. 1957–1964.

[79] Johns, E., Leutenegger, S., and Davison, A. J., 2016. "Deep learning a grasp function for grasping under gripper pose uncertainty". In 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, pp. 4461–4468.

[80] Lenz, I., Lee, H., and Saxena, A., 2015. "Deep learning for detecting robotic grasps". *The International Journal of Robotics Research,* **34**(4-5), pp. 705–724.

[81] Kumbla, N. B., Thakar, S., Kaipa, K. N., Marvel, J., and Gupta, S. K. "Simulation based on-line evaluation of singulation plans to handle perception uncertainty in robotic bin picking". In ASME 2017 12th International Manufacturing Science and Engineering Conference collocated with the JSME/ASME 2017 6th International Conference on Materials and Processing, American Society of Mechanical Engineers Digital Collection.

[82] Kumbla, N. B., Thakar, S., Kaipa, K. N., Marvel, J., and Gupta, S. K., 2018. "Handling perception uncertainty in simulation-based singulation planning for robotic bin picking". *Journal of computing and information science in engineering,* **18**(2).

[83] Yamazaki, K., Tomono, M., Tsubouchi, T., and Yuta, S.-i., 2006. "A grasp planning for picking up an unknown object for a mobile manipulator". In Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006., IEEE, pp. 2143–2149.

[84] Li, Z., Zhao, T., Chen, F., Hu, Y., Su, C.-Y., and Fukuda, T., 2017. "Reinforcement learning of manipulation and grasping using dynamical movement primitives for a humanoidlike mobile manipulator". *IEEE/ASME Transactions on Mechatronics,* **23**(1), pp. 121–131.

[85] Staub, B., Tanwani, A. K., Mahler, J., Breyer, M., Laskey, M., Takaoka, Y., Bajracharya, M., Siegwart, R., and Goldberg, K., 2019. "Dex-net mm: Deep grasping for surface decluttering with a low-precision mobile manipulator". In 2019 IEEE 15th International Conference on Automation Science and Engineering (CASE), IEEE, pp. 1373–1379.

[86] Thakar, S., Rajendran, P., Kabir, A. M., and Gupta, S. K., 2020. "Manipulator motion planning for part pickup and transport operations from a moving base". *IEEE Transactions on Automation Science and Engineering*.

[87] Jangid, H., Jain, S., Teka, B., Raja, R., and Dutta, A., 2020. "Kinematics-based end-effector path control of a mobile manipulator system on an uneven terrain using a two-stage support vector machine". *Robotica,* **38**(8), p. 1415–1433.

[88] Osman, M., Mehrez, M. W., Yang, S., Jeon, S., and Melek, W., 2020. "End-effector stabilization of a 10-dof mobile manipulator using nonlinear model predictive control". *IFAC-PapersOnLine,* **53**(2), pp. 9772–9777. 21th IFAC World Congress.

[89] Galicki, M., 2019. "Optimal cascaded control of mobile manipulators". *Nonlinear Dynamics,* **96**(2), p. 1367–1389.

[90] Miksch, W., and Schroeder, D., 1992. "Performance-functional based controller design for a mobile manipulator". In Proceedings 1992 IEEE International Conference on Robotics and Automation, pp. 227–232 vol.1.

[91] Mishra, S., Londhe, P. S., Mohan, S., Vishvakarma, S. K., and Patre, B. M., 2018. "Robust task-space

motion control of a mobile manipulator using a nonlinear control with an uncertainty estimator". *Comput. Electr. Eng.,* **67**, pp. 729–740.

[92] Pedersen, M. R., Nalpantidis, L., Andersen, R. S., Schou, C., Bøgh, S., Krüger, V., and Madsen, O., 2016. "Robot skills for manufacturing: From concept to industrial deployment". *Robotics and Computer-Integrated Manufacturing,* **37**, pp. 282–291.

[93] Nielsen, I., Dang, Q.-V., Bocewicz, G., and Banaszak, Z., 2017. "A methodology for implementation of mobile robot in adaptive manufacturing environments". *Journal of Intelligent Manufacturing,* **28**(5), pp. 1171–1188.

[94] Andersen, R. E., Hansen, E. B., Cerny, D., Madsen, S., Pulendralingam, B., Bøgh, S., and Chrysostomou, D., 2017. "Integration of a skill-based collaborative mobile robot in a smart cyber-physical environment". *Procedia Manufacturing,* **11**, pp. 114–123.

[95] Deepak, B. B., and Parhi, D. R., 2016. "Control of an automated mobile manipulator using artificial immune system". *J. Exp. Theor. Artif. Intell.,* **28**(1-2), pp. 417–439.

[96] Affan, M., Ahmed, S. U., and Uddin, R., 2020. "Pick-and-Place Task using Wheeled Mobile Manipulator - A Control Design Perspective". *2020 Int. Conf. Comput. Inf. Technol. ICCIT 2020,* **02**, pp. 34–39.

[97] Iriondo, A., Lazkano, E., Susperregi, L., Urain, J., Fernandez, A., and Molina, J., 2019. "Pick and place operations in logistics using a mobile manipulator controlled with deep reinforcement learning". *Appl. Sci.,* **9**(2).

[98] Mar Myint, W., 2015. "Kinematic Control of Pick and Place Robot Arm". *Int. J. Eng. Tech.,* **1**(4), pp. 63–70.

[99] Burridge, R. R., Rizzi, A. A., and Koditschek, D. E., 1995. "Toward a dynamical pick and place". *IEEE Int. Conf. Intell. Robot. Syst.,* **2**, pp. 292–297.

[100] Bicchi, A., and Kumar, V., 2000. "Robotic grasping and contact: A review". *Proceedings-IEEE Int. Conf. Robot. Autom.,* **1**, pp. 348–353.

[101] Kleeberger, K., and Kraus, W., 2020. "Kleeberger2020_Article_ASurveyOnLearning-BasedRobotic.pdf". pp. 239–249.

[102] Nagatani, K., and Yuta, S., 1996. "Designing strategy and implementation of mobile manipulator control system for opening door". *Proc. - IEEE Int. Conf. Robot. Autom.,* **3**(April), pp. 2828–2834.

[103] Dong, W., 2002. "On trajectory and force tracking control of constrained mobile manipulators with parameter uncertainty". *Automatica,* **38**(9), pp. 1475–1484.

[104] Ge, S. S., Wang, Z., and Lee, T. H., 2003. "Adaptive stabilization of uncertain nonholonomic systems by state and output feedback". *Automatica,* **39**(8), pp. 1451–1460.

[105] Korayem, M. H., Azimirad, V., Nikoobin, A., and Boroujeni, Z., 2010. "Maximum load-carrying capacity of autonomous mobile manipulator in an environment with obstacle considering tip over stability". *Int. J. Adv. Manuf. Technol.,* **46**(5-8), pp. 811–829.

[106] Recker, T., Heilemann, F., and Raatz, A., 2020. "Handling of large and heavy objects using a single mobile manipulator in combination with a roller board". *Procedia CIRP,* **97**, pp. 21–26.

[107] Ohashi, F., Kaminishi, K., Figueroa Heredia, J. D., Kato, H., Ogata, T., Hara, T., and Ota, J., 2016. "Realization of heavy object transportation by mobile robots using handcarts and outrigger". *ROBOMECH J.,* **3**(1).

[108] Balatti, P., Fusaro, F., Villa, N., Lamon, E., and Ajoudani, A., 2020. "A Collaborative Robotic Approach to Autonomous Pallet Jack Transportation and Positioning". *IEEE Access,* **8**, pp. 142191–142204.

[109] Yu, S.-N., Ryu, B.-G., Lim, S.-J., Kim, C.-J., Kang, M.-K., and Han, C.-S., 2009. "Feasibility verification of brick-laying robot using manipulation trajectory and the laying pattern optimization". *Automation in Construction,* **18**(5), pp. 644–655.

[110] Knepper, R. A., Layton, T., Romanishin, J., and Rus, D., 2013. "Ikeabot: An autonomous multi-robot coordinated furniture assembly system". In 2013 IEEE International conference on robotics and automation, IEEE, pp. 855–862.

[111] Hamner, B., Koterba, S., Shi, J., Simmons, R., and Singh, S., 2010. "An autonomous mobile manipulator for assembly tasks". *Autonomous Robots,* **28**(1), p. 131.

[112] Bolger, A., Faulkner, M., Stein, D., White, L., Yun, S.-k., and Rus, D., 2010. "Experiments in decentralized robot construction with tool delivery and assembly robots". In 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, pp. 5085–5092.

[113] Lueth, T. C., Nassal, U. M., and Rembold, U., 1995. "Reliability and integrated capabilities of locomotion and manipulation for autonomous robot assembly". *Rob. Auton. Syst.,* **14**(2-3), pp. 185–198.

[114] Minca, E., Filipescu, A., and Voda, A., 2014. "Modelling and control of an assembly/disassembly mechatronics line served by mobile robot with manipulator". *Control Eng. Pract.,* **31**, pp. 50–62.

[115] Yoo, W. S., Kim, J. D., and Na, S. J., 2001. "A study on a mobile platform-manipulator welding system for horizontal fillet joints". *Mechatronics,* **11**(7), pp. 853–868.

[116] Hormann, A., and Rembold, U., 1991. "Development of an advanced robot for autonomous assembly". In Proceedings. 1991 IEEE International Conference on Robotics and Automation, IEEE Computer Society, pp. 2452,2453,2454,2455,2456,2457.

[117] Li, F., Jiang, Q., Quan, W., Song, R., and Li, Y., 2019. "Manipulation skill acquisition for robotic assembly using deep reinforcement learning". *IEEE/ASME Int. Conf. Adv. Intell. Mechatronics, AIM,* **2019-July**, pp. 13–18.

[118] Gibson, I., Rosen, D. W., Stucker, B., et al., 2014. *Additive manufacturing technologies*, Vol. 17. Springer.

[119] Bhatt, P. M., Malhan, R. K., Shembekar, A. V., Yoon, Y. J., and Gupta, S. K., 2020. "Expanding capabilities of additive manufacturing through use of robotics technologies: A survey". *Additive Manufacturing,* **31**, p. 100933.

[120] Yablonina, M., Prado, M., Baharlou, E., Schwinn, T., and Menges, A., 2017. "Mobile robotic fabrication system for filament structures". *Fabricate: Rethinking Design and Construction,* **3**.

[121] John P. Mccrea, Carl R. Hartsfield, J. C., 2018. "Design of A Zero-gravity, Vacuum-based 3D Printer Robot for Use of In-space Satellite Assembly". Aerospace Research Central.

[122] Zhang, X., Li, M., Lim, J. H., Weng, Y., Tay, Y. W. D., Pham, H., and Pham, Q.-C., 2018. "Large-Scale 3D Printing by A Team of Mobile Robots". *Automation in Construction,* **95**, pp. 98–106.

[123] Giftthaler, M., Sandy, T., Dörfler, K., Brooks, I., Buckingham, M., Rey, G., Kohler, M., Gramazio, F., and Buchli, J., 2017. "Mobile robotic fabrication at 1: 1 scale: the in situ fabricator". *Construction Robotics,* **1**(1-4), pp. 3–14.

[124] Peng, J., Yu, J., and Wang, J., 2014. "Robust adaptive tracking control for nonholonomic mobile manipulator with uncertainties". *ISA Trans.,* **53**(4), pp. 1035–1043.

[125] Viet, T. D., Doan, P. T., Hung, N., Kim, H. K., and Kim, S. B., 2012. "Tracking control of a three-wheeled omnidirectional mobile manipulator system with disturbance and friction". *J. Mech. Sci. Technol.,* **26**(7), pp. 2197–2211.

[126] Bhatt, P. M., Rajendran, P., McKay, K., and Gupta, S. K., 2019. "Context-dependent compensation scheme to reduce trajectory execution errors for industrial manipulators". In 2019 International Conference on Robotics and Automation (ICRA), IEEE, pp. 5578–5584.

[127] Danielsen Evjemo, L., Moe, S., Gravdahl, J. T., Roulet-Dubonnet, O., Gellein, L. T., and Brøtan, V., 2017. "Additive manufacturing by robot manipulator: An overview of the state-of-the-art and proof-of-concept results". *IEEE Int. Conf. Emerg. Technol. Fact. Autom. ETFA*(978), pp. 1–8.

[128] Urhal, P., Weightman, A., Diver, C., and Bartolo, P., 2019. "Robot assisted additive manufacturing: A review". *Robot. Comput. Integr. Manuf.,* **59**(July 2018), pp. 335–345.

[129] Bhatt, P. M., Malhan, R. K., Rajendran, P., and Gupta, S. K., 2020. "Building free-form thin shell parts using supportless extrusion-based additive manufacturing". *Additive Manufacturing,* **32**, p. 101003.

[130] Messina, G., Burgassi, S., Messina, D., Montagnani, V., and Cevenini, G., 2015. "A new uv-led device for automatic disinfection of stethoscope membranes". *American journal of infection control,* **43**(10), pp. e61–e66.

[131] Yamamoto, T., Terada, K., Ochiai, A., Saito, F., Asahara, Y., and Murase, K., 2018. "Development of the research platform of a domestic mobile manipulator utilized for international competition and field test". In 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, pp. 7675–7682.

[132] Lu, L., and Wen, J. T., 2017. "Baxter-on-wheels (bow): An assistive mobile manipulator for mobility impaired individuals". In Trends in Control and Decision-Making for Human–Robot Collaboration Systems, Springer, pp. 41–63.

[133] King, C.-H., Chen, T. L., Fan, Z., Glass, J. D., and Kemp, C. C., 2012. "Dusty: an assistive mobile manipulator that retrieves dropped objects for people with motor impairments". *Disability and Rehabilitation: Assistive Technology,* **7**(2), pp. 168–179.

[134] Kapusta, A., Chitalia, Y., Park, D., and Kemp, C. C., 2016. "Collaboration between a robotic bed and a mobile manipulator may improve physical assistance for people with disabilities".

[135] Mersha, A. Y., de Kinkelder, R., and Bekke, D., 2018. "Affordable modular mobile manipulator for domestic applications". In 2018 19th International Conference on Research and Education in Mechatronics (REM), IEEE, pp. 141–146.

[136] Stückler, J., Steffens, R., Holz, D., and Behnke, S., 2013. "Efficient 3d object perception and grasp planning for mobile manipulation in domestic environments". *Robotics and Autonomous Systems,* **61**(10), pp. 1106–1115.

[137] Mitrevski, A., Padalkar, A., Nguyen, M., and Plöger, P. G., 2019. ""lucy, take the noodle box!": Domestic object manipulation using movement primitives and whole body motion". In Robot World Cup, Springer, pp. 189–200.

[138] Qi, N., Zhao, L., Li, R., and Wang, K., 2012. "Dual-arm service robots for mobile operation in indoor environment". In 2012 IEEE International Conference on Mechatronics and Automation, IEEE, pp. 1898–1903.

[139] Mucchiani, C., Cacchione, P., Torres, W., Johnson, M. J., and Yim, M., 2020. "Exploring low-cost mobile manipulation for elder care within a community based setting". *Journal of Intelligent & Robotic Systems,* **98**(1), pp. 59–70.

[140] Yamamoto, T., Terada, K., Ochiai, A., Saito, F., Asahara, Y., and Murase, K., 2019. "Development of human support robot as the research platform of a domestic mobile manipulator". *ROBOMECH journal,* **6**(1), p. 4.

[141] Yamamoto, T., Takagi, Y., Ochiai, A., Iwamoto, K., Itozawa, Y., Asahara, Y., Yokochi, Y., and Ikeda, K., 2019. "Human support robot as research platform of domestic mobile manipulator". In Robot World Cup, Springer, pp. 457–465.

[142] Choi, Y. S., Chen, T., Jain, A., Anderson, C., Glass, J. D., and Kemp, C. C., 2009. "Hand it over or set it down: A user study of object delivery with an assistive mobile manipulator". In RO-MAN 2009-The 18th

IEEE International Symposium on Robot and Human Interactive Communication, IEEE, pp. 736–743.
[143] Lu, L., and Wen, J. T., 2017. "Human-directed coordinated control of an assistive mobile manipulator". *International Journal of Intelligent Robotics and Applications,* **1**(1), pp. 104–120.
[144] Zhou, J., Yan, J., Wei, T., Wu, K., Chen, X., and Hu, S., 2015. "Sharp corner/edge recognition in domestic environments using rgb-d camera systems". *IEEE Transactions on Circuits and Systems II: Express Briefs,* **62**(10), pp. 987–991.
[145] Guo, W., Wang, J., and Chen, W., 2014. "A manipulability improving scheme for opening unknown doors with mobile manipulator". In 2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014), IEEE, pp. 1362–1367.
[146] Chitta, S., Cohen, B., and Likhachev, M., 2010. "Planning for autonomous door opening with a mobile manipulator". In 2010 IEEE International Conference on Robotics and Automation, IEEE, pp. 1799–1806.
[147] Kim, D. W., Kang, J.-H., and Park, G.-T., 2010. "Door-opening behaviour by home service robot in a house". *International Journal of Robotics & Automation,* **25**(4), p. 271.
[148] Kim, D., Kang, J.-H., Hwang, C.-S., and Park, G.-T., 2004. "Mobile robot for door opening in a house". In International Conference on Knowledge-Based and Intelligent Information and Engineering Systems, Springer, pp. 596–602.
[149] Elliott, S., and Cakmak, M., 2018. "Robotic cleaning through dirt rearrangement planning with learned transition models". In 2018 IEEE International Conference on Robotics and Automation (ICRA), IEEE, pp. 1623–1630.
[150] Pan, G., Yang, F., and Chen, M., 2018. "Kinematic control of a dual-arm humanoid mobile cooking robot". In Proceedings of the 12th International Convention on Rehabilitation Engineering and Assistive Technology, Singapore Therapeutic, Assistive & Rehabilitative Technologies (START) Centre, pp. 308–311.
[151] Watanabe, Y., Nagahama, K., Yamazaki, K., Okada, K., and Inaba, M., 2013. "Cooking behavior with handling general cooking tools based on a system integration for a life-sized humanoid robot". *Paladyn, Journal of Behavioral Robotics,* **4**(2), pp. 63–72.
[152] Yamazaki, K., Watanabe, Y., Nagahama, K., Okada, K., and Inaba, M., 2010. "Recognition and manipulation integration for a daily assistive robot working on kitchen environments". In 2010 IEEE International Conference on Robotics and Biomimetics, pp. 196–201.
[153] Yu, H., Li, L., Chen, J., Wang, Y., Wu, Y., Li, M., Li, H., Jiang, Z., Liu, X., and Arai, T., 2019. "Mobile robot capable of crossing floors for library management". In 2019 IEEE International Conference on Mechatronics and Automation (ICMA), IEEE, pp. 2540–2545.
[154] Petersson, L., Austin, D., and Kragic, D., 2000. "High-level control of a mobile manipulator for door opening". *IEEE Int. Conf. Intell. Robot. Syst.,* **3**, pp. 2333–2338.
[155] Li, J., Li, Z., and Hauser, K., 2017. "A study of bidirectionally telepresent tele-action during robot-mediated handover". In 2017 IEEE International Conference on Robotics and Automation (ICRA), IEEE, pp. 2890–2896.
[156] Li, Z., Moran, P., Dong, Q., Shaw, R. J., and Hauser, K., 2017. "Development of a tele-nursing mobile manipulator for remote care-giving in quarantine areas". In 2017 IEEE International Conference on Robotics and Automation (ICRA), IEEE, pp. 3581–3586.
[157] Li, Z., and Hauser, K., 2015. "Ebolabot: Progress toward a tele-nursing robotic system for ebola patient treatment". In RSS 2015 Workshop on Robotics for Advance Response to Epidemics.
[158] Stańczyk, B., Kurnicki, A., and Arent, K., 2016. "Logical architecture of medical telediagnostic robotic system". In 2016 21st International Conference on Methods and Models in Automation and Robotics (MMAR), IEEE, pp. 200–205.
[159] Dasanayake, D., Gunasekara, P., Dabare, S., Wickramasinghe, H., Sandharenu, K., Fernando, S., and Jayasekera, J., 2017. "Smart hospital ward management system with mobile robot wardbot: An efficient management solution for hospital ward".
[160] Dasanayake, D., Gunasekara, P., Wickramasinghe, H., Fernando, S., and Kulasekera, A., 2018. "Automated hospital ward management system interacting with mobile robot platform wdbot". In 2018 IEEE International Conference on Mechatronics and Automation (ICMA), IEEE, pp. 557–562.
[161] Bemelmans, R., Gelderblom, G. J., Jonker, P., and de Witte, L., 2012. "Socially assistive robots in elderly care: A systematic review into effects and effectiveness". *J. Am. Med. Dir. Assoc.,* **13**(2), pp. 114–120.e1.
[162] Martinez-Martin, E., Escalona, F., and Cazorla, M., 2020. "Socially assistive robots for older adults and people with autism: An overview". *Electron.,* **9**(2).
[163] Agah, A., and Tanie, K., 1997. "Human interaction with a service robot: mobile-manipulator handing over an object to a human". In Proceedings of International Conference on Robotics and Automation, Vol. 1, pp. 575–580 vol.1.
[164] Park, D., Hoshi, Y., Mahajan, H. P., Kim, H. K., Erickson, Z., Rogers, W. A., and Kemp, C. C., 2020. "Active robot-assisted feeding with a general-purpose mobile manipulator: Design, evaluation, and lessons learned". *Rob. Auton. Syst.,* **124**, p. 103344.
[165] Li, Z., Moran, P., Dong, Q., Shaw, R. J., and Hauser, K., 2017. "Development of a tele-nursing mobile manipulator for remote care-giving in quarantine areas". *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 3581–3586.
[166] Kapusta, A., Chitalia, Y., Park, D., and Kemp, C. C., 2016. "Collaboration Between a Robotic Bed and

a Mobile Manipulator May Improve Physical Assistance for People with Disabilities".

[167] Kapusta, A. S., Grice, P. M., Clever, H. M., Chitalia, Y., Park, D., and Kemp, C. C., 2019. "A system for bedside assistance that integrates a robotic bed and a mobile manipulator". *PLoS One,* **14**(10), pp. 1–25.

[168] Srinivasa, S. S., Berenson, D., Cakmak, M., Collet, A., Dogar, M. R., Dragan, A. D., Knepper, R. A., Niemueller, T., Strabala, K., Vande Weghe, M., and Ziegler, J., 2012. "Herb 2.0: Lessons learned from developing a mobile manipulator for the home". *Proceedings of the IEEE,* **100**(8), pp. 2410–2428.

[169] , 2017. "Robi': A prototype mobile manipulator for agricultural applications". *Electronics,* **6**(2), p. 39.

[170] Lu, L., and Wen, J. T., 2015. "Human-directed robot motion/force control for contact tasks in unstructured environments". In 2015 IEEE International Conference on Automation Science and Engineering (CASE), pp. 1165–1170.

[171] Wu, X., Wang, Y., and Dang, X., 2014. "Robust adaptive sliding-mode control of condenser-cleaning mobile manipulator using fuzzy wavelet neural network". *Fuzzy Sets and Systems,* **235**, pp. 62–82. Theme: Control and Applications.

[172] Castaman, N., Tosello, E., Antonello, M., Bagarello, N., Gandin, S., Carraro, M., Munaro, M., Bortoletto, R., Ghidoni, S., Menegatti, E., and Pagello, E., 2017. Rur53: an unmanned ground vehicle for navigation, recognition and manipulation.

[173] Bengel, M., Pfeiffer, K., Graf, B., Bubeck, A., and Verl, A., 2009. "Mobile robots for offshore inspection and manipulation". In 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3317–3322.

[174] Ayoade, A. A., 2015. "Navigation and control of a mobile manipulator for inspection". Master's thesis, Colorado School of Mines, 12.

[175] Industries, M. H., 2020. "Development of Robots for Nuclear Power Plants and Their Application to New Fields". pp. 1–12.

[176] Tanigaki, K., Fujiura, T., Akase, A., and Imagawa, J., 2008. "Cherry-harvesting robot". *Computers and Electronics in Agriculture,* **63**(1), pp. 65–72. Special issue on bio-robotics.

[177] Hayashi, S., Shigematsu, K., Yamamoto, S., Kobayashi, K., Kohno, Y., Kamata, J., and Kurita, M., 2010. "Evaluation of a strawberry-harvesting robot in a field test". *Biosystems Engineering,* **105**(2), pp. 160–171.

[178] HAYASHI, S., GANNO, K., ISHII, Y., and TANAKA, I., 2002. "Robotic harvesting system for eggplants". *Japan Agricultural Research Quarterly: JARQ,* **36**(3), pp. 163–168.

[179] ARIMA, S., 1999. "Cucumber harvesting robot and plant training system". *Journal of Robotics and Mechatronics,* **11**(3), pp. 208–212.

[180] Liu, T.-H., Zeng, X.-R., and Ke, Z.-H., 2011. "Design and prototyping a harvester for litchi picking". In 2011 Fourth International Conference on Intelligent Computation Technology and Automation, Vol. 2, pp. 39–42.

[181] Aljanobi, A. A., Al-hamed, S. A., and Al-Suhaibani, S. A., 2010. "A setup of mobile robotic unit for fruit harvesting". In 19th International Workshop on Robotics in Alpe-Adria-Danube Region (RAAD 2010), pp. 105–108.

[182] Nagatani, K., Kiribayashi, S., Okada, Y., Otake, K., Yoshida, K., Tadokoro, S., Nishimura, T., Yoshida, T., Koyanagi, E., Fukushima, M., et al., 2013. "Emergency response to the nuclear accident at the fukushima daiichi nuclear power plants using mobile rescue robots". *Journal of Field Robotics,* **30**(1), pp. 44–63.

[183] Gao, W., Wang, W., Zhu, H., Zhao, S., Huang, G., and Du, Z., 2019. "Irradiation test and hardness design for mobile rescue robot in nuclear environment". *Industrial Robot: the international journal of robotics research and application*.

[184] Takemori, T., Miyake, M., Hirai, T., Wang, X., Fukao, Y., Adachi, M., Yamaguchi, K., Tanishige, S., Nomura, Y., Matsuno, F., et al., 2020. "Development of the multifunctional rescue robot fuhga2 and evaluation at the world robot summit 2018". *Advanced Robotics,* **34**(2), pp. 119–131.

[185] Guarnieri, M., Kurazume, R., Masuda, H., Inoh, T., Takita, K., Debenest, P., Hodoshima, R., Fukushima, E., and Hirose, S., 2009. "Helios system: A team of tracked robots for special urban search and rescue operations". In 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, pp. 2795–2800.

[186] Ohno, K., Morimura, S., Tadokoro, S., Koyanagi, E., and Yoshida, T., 2007. "Semi-autonomous control system of rescue crawler robot having flippers for getting over unknown-steps". In 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, pp. 3012–3018.

[187] Yoshida, T., Nagatani, K., Koyanagi, E., Hada, Y., Ohno, K., Maeyama, S., Akiyama, H., Yoshida, K., and Tadokoro, S., 2010. "Field experiment on multiple mobile robots conducted in an underground mall". In Field and Service robotics, Springer, pp. 365–375.

[188] Casper, J., and Murphy, R. R., 2003. "Human-robot interactions during the robot-assisted urban search and rescue response at the world trade center". *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics),* **33**(3), pp. 367–385.

[189] Teodorescu, M., 2015. This weed destroying tank-bot eliminates the need for chemical pesticide in agriculture, Nov.

[190] Thompson, P., Rabatel, G., Pierrot, F., Liegeois, A., and Sevila, F., 1995. "Performance comparison of various control strategies for a mobile manipulator". In Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots, Vol. 3, pp. 473–479

vol.3.
[191] Writers, T., 2021. Small robot company's first commercial robot 'tom' launches as per-plant weed zapping unveiled, Apr.
[192] Shaw, K. Carbon robotics launches 3rd-generation autonomous weeder robot.
[193] Sturm, J., Engelhard, N., Endres, F., Burgard, W., and Cremers, D., 2012. "A benchmark for the evaluation of rgb-d slam systems". In 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 573–580.
[194] Aguiar, A. S., dos Santos, F. N., Cunha, J. B., Sobreira, H., and Sousa, A. J., 2020. "Localization and mapping for robots in agriculture and forestry: A survey". *Robotics,* **9**(4).
[195] Zhang, Y., Gao, F., and Tian, L., 2008. "Ins/gps integrated navigation for wheeled agricultural robot based on sigma-point kalman filter". In 2008 Asia Simulation Conference - 7th International Conference on System Simulation and Scientific Computing, pp. 1425–1431.
[196] Conceição, T., Neves dos Santos, F., Costa, P., and Moreira, A. P., 2018. "Robot localization system in a hard outdoor environment". In ROBOT 2017: Third Iberian Robotics Conference, A. Ollero, A. Sanfeliu, L. Montano, N. Lau, and C. Cardeira, eds., Springer International Publishing, pp. 215–227.
[197] Bac, C. W., Hemming, J., van Tuijl, B., Barth, R., Wais, E., and van Henten, E. J., 2017. "Performance evaluation of a harvesting robot for sweet pepper". *Journal of Field Robotics,* **34**(6), pp. 1123–1139.
[198] Feng, Q., Zou, W., Fan, P., Zhang, C., and Wang, X., 2018. "Design and test of robotic harvesting system for cherry tomato". *International Journal of Agricultural and Biological Engineering,* **11**(1), p. 96–100.
[199] Kitamura, S., and Oka, K., 2005. "Recognition and cutting system of sweet pepper for picking robot in greenhouse horticulture". In IEEE International Conference Mechatronics and Automation, 2005, Vol. 4, pp. 1807–1812 Vol. 4.
[200] Kusumam, K., Krajník, T., Pearson, S., Duckett, T., and Cielniak, G., 2017. "3d-vision based detection, localization, and sizing of broccoli heads in the field". *Journal of Field Robotics,* **34**(8), pp. 1505–1518.
[201] Onishi, Y., Yoshida, T., Kurita, H., Fukao, T., Arihara, H., and Iwai, A., 2019. "An automated fruit harvesting robot by using deep learning". *ROBOMECH Journal,* **6**(1).
[202] Quaglia, G., Visconte, C., Scimmi, L. S., Melchiorre, M., Cavallone, P., and Pastorelli, S., 2019. "Robot arm and control architecture integration on a ugv for precision agriculture". In Advances in Mechanism and Machine Science, T. Uhl, ed., Springer International Publishing, pp. 2339–2348.
[203] Ponnambalam, V. R., Fentanes, J. P., Das, G., Cielniak, G., Gjevestad, J. G. O., and From, P. J., 2020. "Agri-cost-maps - integration of environmental constraints into navigation systems for agricultural robots". In 2020 6th International Conference on Control, Automation and Robotics (ICCAR), pp. 214–220.
[204] Binch, A., Das, G. P., Pulido Fentanes, J., and Hanheide, M., 2020. "Context dependant iterative parameter optimisation for robust robot navigation". In 2020 IEEE International Conference on Robotics and Automation (ICRA), pp. 3937–3943.
[205] Fue, K., Porter, W., Barnes, E., and Rains, G., 2020. "An extensive review of mobile agricultural robotics for field operations: Focus on cotton harvesting".
[206] Pretto, A., Aravecchia, S., Burgard, W., Chebrolu, N., Dornhege, C., Falck, T., Fleckenstein, F., Fontenla, A., Imperoli, M., Khanna, R., Liebisch, F., Lottes, P., Milioto, A., Nardi, D., Nardi, S., Pfeifer, J., Popovic, M., Potena, C., Pradalier, C., Rothacker-Feder, E., Sa, I., Schaefer, A., Siegwart, R., Stachniss, C., Walter, A., Winterhalter, W., Wu, X., and Nieto, J. I., 2019. "Building an aerial-ground robotics system for precision farming". *CoRR,* **abs/1911.03098**.
[207] Xiong, Y., Ge, Y., Grimstad, L., and From, P. J., 2020. "An autonomous strawberry-harvesting robot: Design, development, integration, and field evaluation". *Journal of Field Robotics,* **37**(2), pp. 202–224.
[208] Fue, K. G., Porter, W. M., Barnes, E. M., and Rains, G. C., 2020. "An extensive review of mobile agricultural robotics for field operations: Focus on cotton harvesting". *AgriEngineering,* **2**(1), pp. 150–174.
[209] Sakai, S., Iida, M., Osuka, K., and Umeda, M., 2008. "Design and control of a heavy material handling manipulator for agricultural robots". *Autonomous Robots,* **25**(3), p. 189–204.
[210] González, R., Fiacchini, M., Guzmán, J. L., Álamo, T., and Rodríguez, F., 2011. "Robust tube-based predictive control for mobile robots in off-road conditions". *Robotics and Autonomous Systems,* **59**(10), pp. 711–726.
[211] Bechar, A., and Vigneault, C., 2016. "Agricultural robots for field operations: Concepts and components". *Biosystems Engineering,* **149**, pp. 94–111.
[212] Bechar, A., and Vigneault, C., 2017. "Agricultural robots for field operations. part 2: Operations and systems". *Biosystems Engineering,* **153**, pp. 110–128.
[213] Hayes-Roth, B., 1985. "A blackboard architecture for control". *Artificial Intelligence,* **26**(3), pp. 251–321.
[214] Nassal, U., Damm, M., and Lüth, T., 1993. "Mobile manipulation — kopplung von mobiler plattform und manipulatoren für ein autonomes robotersystem".
[215] Pin, F., Beckerman, M., Spelt, P., Robinson, J., and Weisbin, C., 1989. "Autonomous mobile robot research using the hermies-iii robot". In Proceedings. IEEE/RSJ International Workshop on Intelligent Robots and Systems '. (IROS '89) 'The Autonomous Mobile Robots and Its Applications, pp. 251–256.
[216] Krotkov, E., Simmons, R., and Whittaker, W., 1995. "Ambler: Performance of a six-legged planetary rover". *Acta Astronautica,* **35**(1), pp. 75–81.
[217] Cardenas, A., Quiroz, O., Hernandez, R., Medellin-

Castillo, H. I., González, A., Maya, M., and Piovesan, D., 2021. "Vision- based control of a mobile manipulator with an adaptable-passive suspension for unstructured environments". *J. Mech. Robot.*, pp. 1–38.

[218] Mbede, J. B., Ele, P., Mveh-Abia, C. M., Toure, Y., Graefe, V., and Ma, S., 2005. "Intelligent mobile manipulator navigation using adaptive neuro-fuzzy systems". *Inf. Sci. (Ny).,* **171**(4), pp. 447–474.

[219] Song, T., Xi, F. J., Guo, S., Tu, X., and Li, X., 2018. "Slip Analysis for a Wheeled Mobile Manipulator". *J. Dyn. Syst. Meas. Control. Trans. ASME,* **140**(2), pp. 1–12.

[220] Liu, Y., and Liu, G., 2009. "Modeling of tracked mobile manipulators with consideration of track-terrain and vehicle-manipulator interactions". *Rob. Auton. Syst.,* **57**(11), pp. 1065–1074.

[221] LaValle, S. M., 2006. *Planning Algorithms*. Cambridge University Press, USA.

[222] Wolfe, J., Marthi, B., and Russell, S., 2010. "Combined task and motion planning for mobile manipulation". In Twentieth International Conference on Automated Planning and Scheduling.

[223] Akbari, A., 2020. "Combining task and motion planning for mobile manipulators".

[224] Cambon, S., Alami, R., and Gravot, F., 2009. "A hybrid approach to intricate motion, manipulation and task planning". *The International Journal of Robotics Research,* **28**(1), pp. 104–126.

[225] Saoji, S., and Rosell, J., 2020. "Flexibly configuring task and motion planning problems for mobile manipulators". In 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Vol. 1, IEEE, pp. 1285–1288.

[226] Thakar, S., Kabir, A., Bhatt, P. M., Malhan, R. K., Rajendran, P., Shah, B. C., and Gupta, S. K., 2019. "Task assignment and motion planning for bi-manual mobile manipulation". In 2019 IEEE 15th International Conference on Automation Science and Engineering (CASE), IEEE, pp. 910–915.

[227] Kabir, A. M., Thakar, S., Bhatt, P. M., Malhan, R. K., Rajendran, P., Shah, B. C., and Gupta, S. K., 2020. "Incorporating motion planning feasibility considerations during task-agent assignment to perform complex tasks using mobile manipulators". In 2020 IEEE International Conference on Robotics and Automation (ICRA), IEEE, pp. 5663–5670.

[228] Kavraki, L. E., Svestka, P., Latombe, J.-C., and Overmars, M. H., 1996. "Probabilistic roadmaps for path planning in high-dimensional configuration spaces". *IEEE transactions on Robotics and Automation,* **12**(4), pp. 566–580.

[229] Rickert, M., Sieverling, A., and Brock, O., 2014. "Balancing exploration and exploitation in sampling-based motion planning". *IEEE Transactions on Robotics,* **30**(6), pp. 1305–1317.

[230] Rajendran, P., Thakar, S., Kabir, A., Shah, B., and Gupta, S. K., 2019. "Context-dependent search for generating paths for redundant manipulators in cluttered environments". In IEEE International Conference on Intelligent Robots and Systems (IROS).

[231] Rajendran, P., Thakar, S., and Gupta, S. K., 2019. "User-guided path planning for redundant manipulators in highly constrained work environments". In 2019 IEEE 15th International Conference on Automation Science and Engineering (CASE), IEEE, pp. 1212–1217.

[232] Rajendran, P., Thakar, S., Bhatt, P. M., Kabir, A. M., and Gupta, S. K., 2021. "Strategies for speeding up manipulator path planning to find high quality paths in cluttered environments". *Journal of Computing and Information Science in Engineering,* **21**(1), p. 011009.

[233] Pilania, V., and Gupta, K., 2014. "A hierarchical and adaptive mobile manipulator planner". In 2014 IEEE-RAS International Conference on Humanoid Robots, IEEE, pp. 45–51.

[234] Li, Q., Mu, Y., You, Y., Zhang, Z., and Feng, C., 2020. "A hierarchical motion planning for mobile manipulator". *IEEJ Transactions on Electrical and Electronic Engineering,* **15**(9), pp. 1390–1399.

[235] Kabir, A. M., Thakar, S., Malhan, R. K., Shembekar, A. V., Shah, B. C., and Gupta, S. K., 2021. "Generation of synchronized configuration space trajectories with workspace path constraints for an ensemble of robots". *The International Journal of Robotics Research*, p. 0278364920988087.

[236] Bodily, D. M., Allen, T. F., and Killpack, M. D., 2017. "Motion planning for mobile robots using inverse kinematics branching". In 2017 IEEE International Conference on Robotics and Automation (ICRA), IEEE, pp. 5043–5050.

[237] Meghdari, A., Naderi, D., On, M. A. . J. S., and undefined 2004, 2004. "Tipover stability estimation for autonomous mobile manipulator using neural network". *Academia.Edu*(July).

[238] Choudhury, S., Gammell, J. D., Barfoot, T. D., Srinivasa, S. S., and Scherer, S., 2016. "Regionally accelerated batch informed trees (rabit*): A framework to integrate local information into optimal path planning". In 2016 IEEE International Conference on Robotics and Automation (ICRA), pp. 4207–4214.

[239] Bowen, C., and Alterovitz, R., 2020. "Accelerating motion planning for learned mobile manipulation tasks using task-guided gibbs sampling". In *Robotics Research*. Springer, pp. 251–267.

[240] Burget, F., Bennewitz, M., and Burgard, W., 2016. "Bi 2 rrt*: An efficient sampling-based path planning framework for task-constrained mobile manipulation". In 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, pp. 3714–3721.

[241] Zhang, H., Sheng, Q., Sun, Y., Sheng, X., Xiong, Z., and Zhu, X., 2020. "A novel coordinated motion planner based on capability map for autonomous mobile manipulator". *Robotics and Autonomous Systems,* **129**, p. 103554.

[242] Pardi, T., Maddali, V., Ortenzi, V., Stolkin, R., and

Marturi, N., 2020. "Path planning for mobile manipulator robots under non-holonomic and task constraints".
[243] Vafadar, S., Olabi, A., and Panahi, M. S., 2018. "Optimal motion planning of mobile manipulators with minimum number of platform movements". In 2018 IEEE International Conference on Industrial Technology (ICIT), IEEE, pp. 262–267.
[244] Zacharias, F., Borst, C., and Hirzinger, G., 2007. "Capturing robot workspace structure: representing robot capabilities". In 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, Ieee, pp. 3229–3236.
[245] Zacharias, F., Sepp, W., Borst, C., and Hirzinger, G., 2009. "Using a model of the reachable workspace to position mobile manipulators for 3-d trajectories". In International Conference on Humanoid Robots, IEEE/RAS, pp. 55–61.
[246] Zacharias, F., Borst, C., Beetz, M., and Hirzinger, G., 2008. "Positioning mobile manipulators to perform constrained linear trajectories". In International Conference on Intelligent Robots and Systems, IEEE/RSJ, pp. 2578–2584.
[247] Malhan, R. K., Kabir, A. M., Shah, B., and Gupta, S. K., 2019. "Identifying feasible workpiece placement with respect to redundant manipulator for complex manufacturing tasks". In International Conference on Robotics and Automation (ICRA), IEEE, pp. 5585–5591.
[248] Malhan, R. K., Kabir, A. M., Shah, B., Centea, T., and Gupta, S. K., 2019. "Determining feasible robot placements in robotic cells for composite prepreg sheet layup". In International Manufacturing Science and Engineering Conference, American Society of Mechanical Engineers Digital Collection (ASME).
[249] Vahrenkamp, N., Asfour, T., and Dillmann, R., 2013. "Robot placement based on reachability inversion". In International Conference on Robotics and Automation, IEEE, pp. 1970–1975.
[250] Makhal, A., and Goins, A. K., 2018. "Reuleaux: Robot base placement by reachability analysis". In International Conference on Robotic Computing (IRC), IEEE, pp. 137–142.
[251] Tang, C. P., and Krovi, V. Manipulability-based configuration evaluation of cooperative payload transport by mobile robot collectives.
[252] Yu, Q., Wang, G., Hua, X., Zhang, S., Song, L., Zhang, J., and Chen, K., 2018. "Base position optimization for mobile painting robot manipulators with multiple constraints". *Robotics and Computer-Integrated Manufacturing,* **54**, pp. 56–64.
[253] Xu, J., Harada, K., Wan, W., Ueshiba, T., and Domae, Y., 2020. "Planning an efficient and robust base sequence for a mobile manipulator performing multiple pick-and-place tasks". In 2020 IEEE International Conference on Robotics and Automation (ICRA), IEEE, pp. 11018–11024.
[254] Dhanaraj, N., Yoon, Y. J., Malhan, R., Bhatt, P. M., Thakar, S., and Gupta, S. K., 2022. "A mobile manipulator system for accurate and efficient spraying on large surfaces". In International Conference on Industry 4.0 and Smart Manufacturing, Elsevier.
[255] Galceran, E., and Carreras, M., 2013. "A survey on coverage path planning for robotics". *Robotics and Autonomous systems,* **61**(12), pp. 1258–1276.
[256] Zhou, J., Zhou, J., Zheng, Y., and Kong, B., 2016. "Research on path planning algorithm of intelligent mowing robot used in large airport lawn". In 2016 International Conference on Information System and Artificial Intelligence (ISAI), pp. 375–379.
[257] Oksanen, T., and Visala, A., 2009. "Coverage path planning algorithms for agricultural field machines". *Journal of field robotics,* **26**(8), pp. 651–668.
[258] Kaljaca, D., Vroegindeweij, B., and van Henten, E., 2020. "Coverage trajectory planning for a bush trimming robot arm". *Journal of Field Robotics,* **37**(2), pp. 283–308.
[259] Sidawi, K., Moroz, P., and Chandra, S., 2021. "On surface area coverage by an electrostatic rotating bell atomizer". *Journal of Coatings Technology and Research*, pp. 1–15.
[260] Yao, Z., and Gupta, S. K., 2004. "Cutter path generation for 2.5 d milling by combining multiple different cutter path patterns". *International journal of production research,* **42**(11), pp. 2141–2161.
[261] Kabir, A. M., Kaipa, K. N., Marvel, J., and Gupta, S. K., 2017. "Automated planning for robotic cleaning using multiple setups and oscillatory tool motions". *IEEE Transactions on Automation Science and Engineering,* **14**(3), pp. 1364–1377.
[262] Olivieri, P., Birglen, L., Maldague, X., and Mantegh, I., 2014. "Coverage path planning for eddy current inspection on complex aeronautical parts". *Robotics and Computer-Integrated Manufacturing,* **30**(3), pp. 305–314.
[263] Glorieux, E., Franciosa, P., and Ceglarek, D., 2020. "Coverage path planning with targetted viewpoint sampling for robotic free-form surface inspection". *Robotics and Computer-Integrated Manufacturing,* **61**, p. 101843.
[264] Wang, Z., and Bo, Z., 2014. "Coverage path planning for mobile robot based on genetic algorithm". In 2014 IEEE Workshop on Electronics, Computer and Applications, IEEE, pp. 732–735.
[265] Paus, F., Kaiser, P., Vahrenkamp, N., and Asfour, T., 2017. "A combined approach for robot placement and coverage path planning for mobile manipulation". In 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, pp. 6285–6292.
[266] Hess, J., Tipaldi, G. D., and Burgard, W., 2012. "Null space optimization for effective coverage of 3d surfaces using redundant manipulators". In 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, pp. 1923–1928.
[267] Yang, T., Miro, J. V., Wang, Y., and Xiong, R., 2020.

"Non-revisiting coverage task with minimal discontinuities for non-redundant manipulators".
[268] Leidner, D., Bejjani, W., Albu-Schäffer, A., and Beetz, M., 2016. "Robotic agents representing, reasoning, and executing wiping tasks for daily household chores". *AUTONOMOUS AGENTS AND MULTI-AGENT SYSTEMS*.
[269] Thakar, S., Malhan, R. K., Bhatt, P. M., and Gupta, S. K., 2021. "Area-coverage planning for spray-based surface disinfection with a mobile manipulator". *Robotics and Autonomous Systems*, p. 103920.
[270] Chen, F., Selvaggio, M., and Caldwell, D. G., 2018. "Dexterous grasping by manipulability selection for mobile manipulator with visual guidance". *IEEE Transactions on Industrial Informatics,* **15**(2), pp. 1202–1210.
[271] Yamazaki, K., Tomono, M., and Tsubouchi, T., 2006. "Motion planning for a mobile manipulator with several grasping postures.". In ROBIO, pp. 1077–1082.
[272] Suzuki, S., Endo, D., and Yamazaki, K., 2021. "Posture evaluation for mobile manipulators using manipulation ability, tolerance on grasping, and pose error of end-effector". *Advanced Robotics*, pp. 1–16.
[273] Fujita, Y., Uenishi, K., Ummadisingu, A., Nagarajan, P., Masuda, S., and Castro, M. Y., 2020. "Distributed reinforcement learning of targeted grasping with active vision for mobile manipulators". *arXiv preprint arXiv:2007.08082*.
[274] Mahler, J., Matl, M., Liu, X., Li, A., Gealy, D., and Goldberg, K., 2018. "Dex-net 3.0: Computing robust vacuum suction grasp targets in point clouds using a new analytic model and deep learning". In 2018 IEEE International Conference on Robotics and Automation (ICRA), IEEE, pp. 1–8.
[275] Mahler, J., Matl, M., Satish, V., Danielczuk, M., DeRose, B., McKinley, S., and Goldberg, K., 2019. "Learning ambidextrous robot grasping policies". *Science Robotics,* **4**(26).
[276] Hegedus, M., Gupta, K., and Mehrandezh, M., 2019. "Towards an integrated autonomous data-driven grasping system with a mobile manipulator". In 2019 International Conference on Robotics and Automation (ICRA), pp. 1601–1607.
[277] Chen, D., Liu, Z., and von Wichert, G., 2013. "Grasping on the move: A generic arm-base coordinated grasping pipeline for mobile manipulation". In 2013 European Conference on Mobile Robots, IEEE, pp. 349–354.
[278] Souissi, O., Benatitallah, R., Duvivier, D., Artiba, A., Belanger, N., and Feyzeau, P., 2013. "Path planning: A 2013 survey". *Proc. 2013 Int. Conf. Ind. Eng. Syst. Manag. IEEE - IESM 2013,* **2013**(October).
[279] Muralidharan, V., and Mahindrakar, A. D., 2014. "Position stabilization and waypoint tracking control of mobile inverted pendulum robot". *IEEE Trans. Control Syst. Technol.,* **22**(6), pp. 2360–2367.
[280] Gutiérrez, R., López-Guillén, E., Bergasa, L. M., Barea, R., Pérez, Ó., Gómez-Huélamo, C., Arango, F., Del Egido, J., and López-Fernández, J., 2020. "A waypoint tracking controller for autonomous road vehicles using ROS framework". *Sensors (Switzerland),* **20**(14).
[281] Mathew, R., and Hiremath, S. S., 2019. "Development of waypoint tracking controller for differential drive mobile robot". *2019 6th Int. Conf. Control. Decis. Inf. Technol. CoDIT 2019*, pp. 1121–1126.
[282] Arai, H., Tanie, K., and Tachi, S., 1992. "Path Tracking Control of A Manipulator Considering Torque Saturation". *IEEE Int. Conf. Intell. Robot. Syst.,* **2**(1), pp. 1004–1009.
[283] Jin, J., and Gong, J., 2021. "An interference-tolerant fast convergence zeroing neural network for dynamic matrix inversion and its application to mobile manipulator path tracking". *Alexandria Eng. J.,* **60**(1), pp. 659–669.
[284] Karray, A., and Feki, M., 2014. "Adaptive tracking control of a mobile manipulator actuated by DC motors". *Int. J. Model. Identif. Control,* **21**(2), pp. 193–201.
[285] Zheng, Y., and Anubi, O. M., 2020. "Attack-resilient observer pruning for path-tracking control of wheeled mobile robot". *ASME 2020 Dyn. Syst. Control Conf. DSCC 2020,* **2**, pp. 1–9.
[286] Zhong, G., Kobayashi, Y., Hoshino, Y., and Emaru, T., 2013. "System modeling and tracking control of mobile manipulator subjected to dynamic interaction and uncertainty". *Nonlinear Dyn.,* **73**(1-2), pp. 167–182.
[287] Iran, T. P., Chung, T. L., Kim, H. K., Kim, S. B., and Oh, M. S., 2004. "Trajectory tracking of mobile manipulator for welding task using sliding mode control". In 30th Annual Conference of IEEE Industrial Electronics Society, 2004. IECON 2004, Vol. 1, pp. 407–412 Vol. 1.
[288] Xiao, L., Liao, B., Li, S., Zhang, Z., Ding, L., and Jin, L., 2018. "Design and Analysis of FTZNN Applied to the Real-Time Solution of a Nonstationary Lyapunov Equation and Tracking Control of a Wheeled Mobile Manipulator". *IEEE Trans. Ind. Informatics,* **14**(1), pp. 98–105.
[289] Khan, A. H., Li, S., Chen, D., and Liao, L., 2020. "Tracking control of redundant mobile manipulator: An RNN based metaheuristic approach". *Neurocomputing,* **400**, pp. 272–284.
[290] Mashali, M., Wu, L., Alqasemi, R., and Dubey, R., 2018. "Controlling a Non-Holonomic Mobile Manipulator in a Constrained Floor Space". *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 725–731.
[291] Dačić, D. B., and Kokotović, P. V., 2006. "Path-following for linear systems with unstable zero dynamics". *Automatica,* **42**(10), pp. 1673–1683.
[292] Aguiar, A. P., Dačić, D. B., Hespanha, J. P., and Kokotović, P., 2004. "Path-following or reference tracking?". *IFAC Proc. Vol.,* **37**(8), pp. 167–172.
[293] Abdessemed, F., and Monacelli, E., 2009. *An alternate control strategy of a mobile manipulator with*

hardware and software description, Vol. 14. IFAC.

[294] Liu, K., and Lewis, F. L., 1992. "Application of robust control techniques to a mobile robot system". *Journal of Robotic Systems,* **9**(7), p. 893–913.

[295] Chung, J. H., Velinsky, S. A., and Hess, R. A., 1998. "Interaction control of a redundant mobile manipulator". *The International Journal of Robotics Research,* **17**(12), p. 1302–1309.

[296] TAN, T. P., THIEN, P. T., TRONG, H. B., and SANG, B. K., 2004. "Decentralized control method for a welding mobile manipulator". *Advances in Dynamics, Instrumentation and Control*.

[297] Gong, K., and McInnes, A. I., 2013. "A modular hierarchical control scheme for mobile manipulation". *Recent Advances in Robotics and Automation*, p. 243–261.

[298] He, Y., Wu, M., and Liu, S., 2018. "Decentralised cooperative mobile manipulation with adaptive control parameters". In 2018 IEEE Conference on Control Technology and Applications (CCTA), pp. 82–87.

[299] Silva, F. F. A., and Adorno, B. V., 2016. "Whole-body control of a mobile manipulator using feedback linearization based on dual quaternions". In 2016 XIII Latin American Robotics Symposium and IV Brazilian Robotics Symposium (LARS/SBR), pp. 293–298.

[300] Papadopoulos, E., and Poulakakis, J., 2000. "Planning and model-based control for mobile manipulators". In Proceedings. 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2000) (Cat. No.00CH37113), Vol. 3, pp. 1810–1815 vol.3.

[301] Merkt, W., Ivan, V., Yang, Y., and Vijayakumar, S., 2019. "Towards shared autonomy applications using whole-body control formulations of locomanipulation". In 2019 IEEE 15th International Conference on Automation Science and Engineering (CASE), pp. 1206–1211.

[302] Yamamoto, Y., and Yun, X., 1992. "Coordinating locomotion and manipulation of a mobile manipulator". In [1992] Proceedings of the 31st IEEE Conference on Decision and Control, pp. 2643–2648 vol.3.

[303] Krasinskii, A. Y., Il'ina, A. N., and Krasinskaya, E. M., 2019. "Stabilization of Steady Motions for Systems with Redundant Coordinates". *Moscow Univ. Mech. Bull.,* **74**(1), pp. 14–19.

[304] Mbakop, S., Tagne, G., Lakhal, O., Merzouki, R., and Drakunov, S. V., 2020. "Path planning and control of mobile soft manipulators with obstacle avoidance". In 2020 3rd IEEE International Conference on Soft Robotics (RoboSoft), pp. 64–69.

[305] Lim, J., Lee, J., Lee, C., Kim, G., Cha, Y., Sim, J., and Rhim, S., 2021. "Designing path of collision avoidance for mobile manipulator in worker safety monitoring system using reinforcement learning". In 2021 IEEE International Conference on Intelligence and Safety for Robotics (ISR), pp. 94–97.

[306] Kot, T., Krys, V., Mostýn, V., and Novák, P., 2014. "Control system of a mobile robot manipulator". In Proceedings of the 2014 15th International Carpathian Control Conference (ICCC), pp. 258–263.

[307] Cameron, J., MacKenzie, D., Ward, K., Arkin, R., and Book, W., 1993. "Reactive control for mobile manipulation". In [1993] Proceedings IEEE International Conference on Robotics and Automation, pp. 228–235 vol.3.

[308] Li, M., Yang, Z., Zha, F., Wang, X., Wang, P., Li, P., Ren, Q., and Chen, F., 2020. "Design and analysis of a whole-body controller for a velocity controlled robot mobile manipulator". *Sci. China Inf. Sci.,* **63**(7), pp. 1–15.

[309] Huang, Q., Sugano, S., and Kato, I., 1994. "Stability control for a mobile manipulator using a potential method". In Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'94), Vol. 2, pp. 839–846 vol.2.

[310] Liu, Y.-H., Meng, X.-C., and Zhang, M.-L., 2008. "Research on mobile manipulator tip-over stability and compensation". In Proceedings of the 8th WSEAS International Conference on Robotics, Control and Manufacturing Technology, ROCOM'08, World Scientific and Engineering Academy and Society (WSEAS), p. 114–120.

[311] Moosavian, S. A. A., and Alipour, K., 2007. "On the dynamic tip-over stability of wheeled mobile manipulators". *Int. J. Robot. Autom.,* **22**(4), Sept., p. 322–328.

[312] HUANG, Q., SUGANO, S., and KATO, I., 1995. "Stability control for a vehicle-mounted manipulator". *Transactions of the Society of Instrument and Control Engineers,* **31**(7), pp. 861–870.

[313] Shihabudheen, K. V., George, N., and Dileep, G., 2015. "Applying h-infinity for stability control in two wheeled mobile manipulator". In 2015 International Conference on Soft Computing Techniques and Implementations (ICSCTI), pp. 46–51.

[314] Huang, Q., Tanie, K., and Sugano, S., 1998. "Stability compensation of a mobile manipulator by manipulatorpaper motion: feasibility and planning". *Advanced Robotics,* **13**(1), pp. 25–40.

[315] Papadopoulos, E., and Rey, D., 1996. "A new measure of tipover stability margin for mobile manipulators". In Proceedings of IEEE International Conference on Robotics and Automation, Vol. 4, pp. 3111–3116 vol.4.

[316] Bertagnoli, M., 2017. "Model-based stability analysis for mobile manipulators". Master's thesis, Ostbayerische Technische Hochschule Regensburg, 6.

[317] Diaz-Calderon, A., and Kelly, A., 2005. "On-line stability margin and attitude estimation for dynamic articulating mobile robots". *The International Journal of Robotics Research,* **24**(10), pp. 845–866.

[318] Mailah, M., Pitowarno, E., and Jamaluddin, H., 2005. "Robust motion control for mobile manipulator using resolved acceleration and proportional-integral active force control". *International Journal of Advanced Robotic Systems,* **2**(2), p. 14.

[319] Ram, R. V., Pathak, P. M., and Junco, S. J., 2019.

"Trajectory control of a mobile manipulator in the presence of base disturbance". *Simulation,* **95**(6), pp. 529–543.

[320] Mathew, S. S., and Jisha, V. R., 2020. "Tracking Control of a Mobile Manipulator with External Torque Disturbances Using Computed Torque Control". *2020 IEEE 17th India Counc. Int. Conf. INDICON 2020*, pp. 1–7.

[321] Spong, M. W., Thorp, J. S., and Kleinwaks, J. M., 1984. "The control of robot manipulators with bounded input: Part ii: Robustness and disturbance rejection". In The 23rd IEEE Conference on Decision and Control, pp. 1047–1052.

[322] Liu, D., Gao, Q., Chen, Z., and Liu, Z., 2020. "Linear active disturbance rejection control of a two-degrees-of-freedom manipulator". *Mathematical Problems in Engineering,* **2020**, p. 1–19.

[323] , 2017. Trajectory Tracking Control for a Robotic Manipulator Using Nonlinear Active Disturbance Rejection Control, Vol. Volume 2: Mechatronics; Estimation and Identification; Uncertain Systems and Robustness; Path Planning and Motion Control; Tracking Control Systems; Multi-Agent and Networked Systems; Manufacturing; Intelligent Transportation and Vehicles; Sensors and Actuators; Diagnostics and Detection; Unmanned, Ground and Surface Robotics; Motion and Vibration Control Applications of *Dynamic Systems and Control Conference*. V002T12A002.

[324] Jing, C., Xu, H., and Niu, X., 2019. "Adaptive sliding mode disturbance rejection control with prescribed performance for robotic manipulators". *ISA Transactions,* **91**, pp. 41–51.

[325] Mousazadeh, H., 2013. "A technical review on navigation systems of agricultural autonomous off-road vehicles". *Journal of Terramechanics,* **50**(3), pp. 211–232.

[326] Park, C., Park, D., Jung, G., Kim, D., Park, K., Park, C., and Choi, T., 2014. "A robot manipulator on the mobile platform for an off-road environment". In 2014 14th International Conference on Control, Automation and Systems (ICCAS 2014), pp. 322–325.

[327] Habibnejad Korayem, M., Ghobadi, N., and Fathollahi Dehkordi, S., 2021. "Designing an optimal control strategy for a mobile manipulator and its application by considering the effect of uncertainties and wheel slipping". *Optimal Control Applications and Methods*.

[328] Chung, J. H., and Velinsky, S. A., 1998. "Modeling and control of a mobile manipulator". *Robotica,* **16**(6), p. 607–613.

[329] Chitta, S., Jones, E. G., Ciocarlie, M., and Hsiao, K., 2012. "Perception, planning, and execution for mobile manipulation in unstructured environments". *IEEE Robotics and Automation Magazine, Special Issue on Mobile Manipulation,* **19**(2), pp. 58–71.

[330] Blomqvist, K., Breyer, M., Cramariuc, A., Förster, J., Grinvald, M., Tschopp, F., Chung, J. J., Ott, L., Nieto, J. I., and Siegwart, R., 2020. "Go fetch: Mobile manipulation in unstructured environments". *CoRR,* **abs/2004.00899**.

[331] Pane, Y. P., Nageshrao, S. P., Kober, J., and Babuška, R., 2019. "Reinforcement learning based compensation methods for robot manipulators". *Eng. Appl. Artif. Intell.,* **78**(November 2018), pp. 236–247.

[332] Jin, L., Li, S., Yu, J., and He, J., 2018. "Robot manipulator control using neural networks: A survey". *Neurocomputing,* **285**, pp. 23–34.

[333] Polydoros, A. S., and Nalpantidis, L., 2017. "Survey of Model-Based Reinforcement Learning: Applications on Robotics". *J. Intell. Robot. Syst. Theory Appl.,* **86**(2), pp. 153–173.

[334] Silva Ortigoza, R., Marcelino-Aranda, M., Silva Ortigoza, G., Hernandez Guzman, V. M., Molina-Vilchis, M. A., Saldana-Gonzalez, G., Herrera-Lozada, J. C., and Olguin-Carbajal, M., 2012. "Wheeled mobile robots: A review". *IEEE Lat. Am. Trans.,* **10**(6), pp. 2209–2217.

[335] Leena, N., and Saju, K., 2016. "Modelling and Trajectory Tracking of Wheeled Mobile Robots". *Procedia Technol.,* **24**, pp. 538–545.

[336] Aly, A., and Salem, F., 2013. "Vehicle suspension systems control: a review". *Int. J. Control. Autom. Syst.,* **2**(2), pp. 46–54.

[337] Hootsmans, N. A., and Dubowsky, S., 1991. "Large motion control of mobile manipulators including vehicle suspension characteristics". *Proc. - IEEE Int. Conf. Robot. Autom.,* **3**, pp. 2336–2341.

[338] Nozaki, K., and Murakami, T., 2009. "A motion control of two-wheels driven mobile manipulator for human-robot cooperative transportation". *IECON Proc. (Industrial Electron. Conf.*, pp. 1574–1579.

[339] Chan, R. P. M., Stol, K. A., and Halkyard, C. R., 2013. "Review of modelling and control of two-wheeled robots". *Annu. Rev. Control,* **37**(1), pp. 89–103.

[340] Dombre, E., and Khalil, W., 2013. *Robot Manipulators: Modeling, Performance Analysis and Control*. Wiley.

[341] Sciavicco, L., and Siciliano, B., 2000. *Modelling and control of robot manipulators*. Springer.

[342] Siciliano, B., and Khatib, O., 2016. *Springer handbook of robotics*.

[343] Watanabe, K., Sato, K., Izumi, K., and Kunitake, Y., 2000. "Analysis and control for an omnidirectional mobile manipulator". *J. Intell. Robot. Syst. Theory Appl.,* **27**(1-2), pp. 3–20.

[344] Xu, D., Zhao, D., and Yi, J., 2007. "Dynamic model and control for an omnidirectional mobile manipulator". *Lect. Notes Control Inf. Sci.,* **362**, pp. 21–30.

[345] Karavaev, Y. L., Shestakov, V. A., and Yefremov, K. S., 2019. "Experimental investigations of the control algorithm of a mobile manipulation robot". *Russ. J. Nonlinear Dyn.,* **15**(4), pp. 487–495.

[346] Aguilera, S., Torres-Torriti, M., and Auat, F., 2014. "Modeling of skid-steer mobile manipulators using spatial vector algebra and experimental validation

with a compact loader". *IEEE Int. Conf. Intell. Robot. Syst.*(Iros), pp. 1649–1655.

[347] Tchoń, K., Jakubiak, J., and Muszyński, R., 2001. "Kinematics of mobile manipulators: a control theoretic perspective". *Archives of Control Sciences,* **11**(3/4), pp. 195–221.

[348] Bayle, B., Fourquet, J. Y., and Renaud, M., 2003. "Manipulability of wheeled mobile manipulators: Application to motion generation". *Int. J. Rob. Res.,* **22**(7-8 SPECIAL ISSUE), pp. 565–581.

[349] Vázquez, A., Velasco-Villa, M., and Del-Muro-Cuellar, B., 2008. "Path-tracking dynamic model based control of an omnidirectional mobile robot". *IFAC Proc. Vol.,* **17**(1 PART 1), pp. 5365–5370.

[350] Padois, V., Fourquet, J. Y., and Chiron, P., 2007. "Kinematic and dynamic model-based control of wheeled mobile manipulators: A unified framework for reactive approaches". *Robotica,* **25**(2), pp. 157–173.

[351] Abdullah, S., Mailah, M., and Hing, C. T. H., 2013. "Feedforward model based active force control of mobile manipulator using MATLAB and MD adams". *WSEAS Trans. Syst.,* **12**(6), pp. 314–324.

[352] Papadopoulos, E., and Poulakakis, J., 2000. "Planning and model-based control for mobile manipulators". *IEEE Int. Conf. Intell. Robot. Syst.,* **3**, pp. 1810–1815.

[353] Avanzini, G. B., Zanchettin, A. M., and Rocco, P., 2015. "Constraint-based Model Predictive Control for holonomic mobile manipulators". *IEEE Int. Conf. Intell. Robot. Syst.,* **2015-Decem**(i), pp. 1473–1479.

[354] Minniti, M. V., Farshidian, F., Grandia, R., and Hutter, M., 2019. "Whole-Body MPC for a Dynamically Stable Mobile Manipulator". *IEEE Robot. Autom. Lett.,* **4**(4), pp. 3687–3694.

[355] Wang, Y., Kusano, H., and Sugihara, T., 2021. "Transporting a heavy object on a frictional floor by a mobile manipulator based on adaptive MPC framework". *2021 IEEE/SICE Int. Symp. Syst. Integr. SII 2021*, pp. 807–812.

[356] Colombo, R., Gennari, F., Annem, V., Rajendran, P., Thakar, S., Bascetta, L., and Gupta, S. K., 2019. "Parameterized model predictive control of a nonholonomic mobile manipulator: A terminal constraint-free approach". In 2019 IEEE 15th International Conference on Automation Science and Engineering (CASE), IEEE, pp. 1437–1442.

[357] Tan, J., and Xi, N., 2002. "Integrated task planning and control for mobile manipulators". In Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No.02CH37292), Vol. 1, pp. 382–387 vol.1.

[358] Khatib, O., 1999. "Mobile manipulation: The robotic assistant". *Robotics and Autonomous Systems,* **26**(2), pp. 175–183. Field and Service Robotics.

[359] John Hollerbach, Wisama Khalil, M. G., 2016. "Model Identification". *Springer Handb. Robot.*, pp. 113–137.

[360] Peters, J., Lee, D. D., Kober, J., Nguyen-tuong, D., Bagnell, J. A., and Schaal, S. "Robot Learning, Springer Handbook of Robotics". pp. 357–394.

[361] Cao, Z., and Niu, Y., 2018. "Finite-time sliding mode control of Markovian jump systems subject to actuator nonlinearities and its application to wheeled mobile manipulator". *J. Franklin Inst.,* **355**(16), pp. 7865–7894.

[362] Seo, I. S., and Han, S. I., 2018. "Dual closed-loop sliding mode control for a decoupled three-link wheeled mobile manipulator". *ISA Trans.,* **80**(July), pp. 322–335.

[363] Peng, J., Yang, Z., Wang, Y., Zhang, F., and Liu, Y., 2019. "Robust adaptive motion/force control scheme for crawler-type mobile manipulator with nonholonomic constraint based on sliding mode control approach". *ISA Trans.,* **92**, pp. 166–179.

[364] Brahmi, A., Saad, M., Gauthier, G., Zhu, W. H., and Ghommam, J., 2017. "Tracking control of mobile manipulator robot based on adaptive backstepping approach". *International Journal of Digital Signals and Smart Systems,* **1**(3), p. 224.

[365] Chen, N., Song, F., Li, G., Sun, X., and Ai, C., 2013. "An adaptive sliding mode backstepping control for the mobile manipulator with nonholonomic constraints". *Commun. Nonlinear Sci. Numer. Simul.,* **18**(10), pp. 2885–2899.

[366] Bu, C. W., and Xu, K. F., 2009. "Robust control of mobile manipulator service robot using torque compensation". *Proc. - 2009 Int. Conf. Inf. Technol. Comput. Sci. ITCS 2009,* **2**, pp. 69–72.

[367] Andaluz, V., Roberti, F., and Carelli, R., 2010. "Robust control with redundancy resolution and dynamic compensation for mobile manipulators". *Proc. IEEE Int. Conf. Ind. Technol.,* **1109**(5400), pp. 1469–1474.

[368] Mazur, A., 2004. "Hybrid adaptive control laws solving a path following problem for non-holonomic mobile manipulators". *Int. J. Control,* **77**(15), pp. 1297–1306.

[369] Nguyen, T. P., Vo, H. D., Joon, H. J., Hak, K. K., and Sang, B. K., 2007. "Adaptive control for welding mobile manipulator with unknown dimensional parameters". *Proc. 2007 4th IEEE Int. Conf. Mechatronics, ICM 2007*(May), pp. 8–10.

[370] Andaluz, V., Roberti, F., and Carelli, R., 2010. "Adaptive control with redundancy resolution of mobile manipulators". *IECON Proc. (Industrial Electron. Conf.,* **1109**(5400), pp. 1436–1441.

[371] Ding, L., Xia, K., Gao, H., Liu, G., and Deng, Z., 2018. "Robust adaptive control of door opening by a mobile rescue manipulator based on unknown-force-related constraints estimation". *Robotica,* **36**(1), pp. 119–140.

[372] Li, Z., Ge, S. S., Adams, M., and Wijesoma, W. S., 2008. "Robust adaptive control of uncertain force/motion constrained nonholonomic mobile manipulators". *Automatica,* **44**(3), pp. 776–784.

[373] Boukattaya, M., Damak, T., and Jallouli, M., 2011.

"Robust adaptive control for mobile manipulators". *Int. J. Autom. Comput.,* **8**(1), pp. 8–13.

[374] Ge, S. S., Wang, J., Lee, T. H., and Zhou, G. Y., 2001. "Adaptive robust stabilization of dynamic nonholonomic chained systems". *J. Robot. Syst.,* **18**(3), pp. 119–133.

[375] Wang, Z., Ge, S., and Lee, T., 2004. "Robust motion/force control of uncertain holonomic/nonholonomic mechanical systems". *IEEE/ASME Transactions on Mechatronics,* **9**(1), pp. 118–123.

[376] Peters, J., Lee, D. D., Kober, J., Nguyen-Tuong, D., Bagnell, J. A., and Schaal, S., 2016. *Robot Learning*. Springer International Publishing, Cham, pp. 357–398.

[377] Nassal, U., and Junge, R., 1996. "Fuzzy control for mobile manipulation". In Proceedings of IEEE International Conference on Robotics and Automation, Vol. 3, pp. 2264–2269 vol.3.

[378] ERDEN, M. S., LEBLEBICIOĞLU, K., and HALICI, U., 2002. "Multi-agent system based fuzzy controller design with genetic tuning for a service mobile manipulator robot in the hand-over task". *IFAC Proceedings Volumes,* **35**(1), pp. 503–508. 15th IFAC World Congress.

[379] Azar, A. T., Ammar, H. H., and Mliki, H., 2018. "Fuzzy logic controller with color vision system tracking for mobile manipulator robot". In The International Conference on Advanced Machine Learning Technologies and Applications (AMLTA2018), A. E. Hassanien, M. F. Tolba, M. Elhoseny, and M. Mostafa, eds., Springer International Publishing, pp. 138–146.

[380] Wang, C., Zhang, Q., Tian, Q., Li, S., Wang, X., Lane, D., Petillot, Y., and Wang, S., 2020. "Learning mobile manipulation through deep reinforcement learning". *Sensors (Switzerland),* **20**(3), pp. 1–18.

[381] Kindle, J., Furrer, F., Novkovic, T., Chung, J. J., Siegwart, R., and Nieto, J., 2020. "Whole-Body Control of a Mobile Manipulator using End-to-End Reinforcement Learning".

[382] Li, Z., Zhao, T., Chen, F., Hu, Y., Su, C. Y., and Fukuda, T., 2018. "Reinforcement Learning of Manipulation and Grasping Using Dynamical Movement Primitives for a Humanoidlike Mobile Manipulator". *IEEE/ASME Trans. Mechatronics,* **23**(1), pp. 121–131.

[383] Honerkamp, D., Welschehold, T., and Valada, A., 2021. "Learning Kinematic Feasibility for Mobile Manipulation through Deep Reinforcement Learning".

[384] Lin, S., and Goldenberg, A. A., 2001. "Neural-network control of mobile manipulators". *IEEE Trans. Neural Networks,* **12**(5), pp. 1121–1133.

[385] Lee, C. Y., Jeong, I. K., Lee, I. H., and Lee, J. J., 2004. "Motion control of mobile manipulator based on neural networks and error compensation". *Proc. - IEEE Int. Conf. Robot. Autom.,* **2004**(5), pp. 4627–4632.

[386] Yi, G., Mao, J., Wang, Y., Guo, S., and Miao, Z., 2018. "Adaptive Tracking Control of Nonholonomic Mobile Manipulators Using Recurrent Neural Networks". *Int. J. Control. Autom. Syst.,* **16**(3), pp. 1390–1403.

[387] Ren, C., Zhang, J., Li, W., and Ma, S., 2020. "Data-driven model free adaptive control for an omnidirectional mobile manipulator using neural network". In 2020 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), pp. 1002–1007.

[388] Teka, B., Raja, R., and Dutta, A., 2019. "Learning based end effector tracking control of a mobile manipulator for performing tasks on an uneven terrain". *International Journal of Intelligent Robotics and Applications,* **3**(2), p. 102–114.

[389] Meng, J., Wang, S., Li, G., Jiang, L., Zhang, X., Liu, C., and Xie, Y., 2021. "Iterative-learning error compensation for autonomous parking of mobile manipulator in harsh industrial environment". *Robot. Comput. Integr. Manuf.,* **68**(November 2019), p. 102077.

[390] Mai, T., 2021. "Hybrid adaptive tracking control method for mobile manipulator robot based on proportional–integral–derivative technique". *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*.

[391] Cheng, M.-B., and Tsai, C.-C., 2005. "Hybrid robust tracking control for a mobile manipulator via sliding-mode neural network". In IEEE International Conference on Mechatronics, 2005. ICM '05., pp. 537–542.

[392] Cheng, M. B., and Tsai, C. C., 2005. "Hybrid sliding-mode fuzzy neural network tracking control for a wheeled mobile manipulator". *Proc. IEEE Int. Conf. Ind. Technol.,* **2005**, pp. 944–949.

[393] WEI, W., 2003. "Neuro-fuzzy and model-based motion control for mobile manipulator among dynamic obstacles". *Sci. China Ser. F,* **46**(1), p. 14.

[394] Mbede, J., Ma, S., Toure, Y., Graefe, V., and Zhang, L., 2004. "Robust neuro-fuzzy navigation of mobile manipulator among dynamic obstacles". In IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004, Vol. 5, pp. 5051–5057.

[395] Kumar, N., Panwar, V., Sukavanam, N., Sharma, S. P., and Borm, J. H., 2011. "Neural network based hybrid force/position control for robot manipulators". *Int. J. Precis. Eng. Manuf.,* **12**(3), pp. 419–426.

[396] Xia, K., Gao, H., Ding, L., Liu, G., Deng, Z., Liu, Z., and Ma, C., 2018. "Trajectory tracking control of wheeled mobile manipulator based on fuzzy neural network and extended Kalman filtering". *Neural Comput. Appl.,* **30**(2), pp. 447–462.

[397] Navarro, B., Cherubini, A., Fonte, A., Poisson, G., and Fraisse, P., 2017. "A framework for intuitive collaboration with a mobile manipulator". In 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, pp. 6293–6298.

[398] Sisbot, E. A., Clodic, A., Alami, R., and Ransan, M.,

2008. "Supervision and motion planning for a mobile manipulator interacting with humans". In Proceedings of the 3rd ACM/IEEE international conference on Human robot interaction, pp. 327–334.

[399] Agah, A., and Tanie, K., 1997. "Human interaction with a service robot: Mobile-manipulator handing over an object to a human". In Proceedings of International Conference on Robotics and Automation, Vol. 1, IEEE, pp. 575–580.

[400] Yamamoto, Y., Eda, H., and Yun, X., 1996. "Coordinated task execution of a human and a mobile manipulator". In Proceedings of IEEE International Conference on Robotics and Automation, Vol. 2, IEEE, pp. 1006–1011.

[401] Al-Hussaini, S., Thakar, S., Kim, H., Rajendran, P., Shah, B. C., Marvel, J. A., and Gupta, S. K., 2020. "Human-supervised semi-autonomous mobile manipulators for safely and efficiently executing machine tending tasks". In Artificial Intelligence for Human-Robot Interaction Symposium, AAAI Fall Symposium Series.

[402] Chen, M., Liu, C., and Du, G., 2018. "A human–robot interface for mobile manipulator". *Intelligent Service Robotics,* **11**(3), pp. 269–278.

[403] Andaluz, V. H., Quevedo, W. X., Chicaiza, F. A., Varela, J., Gallardo, C., Sánchez, J. S., and Arteaga, O., 2016. "Transparency of a bilateral tele-operation scheme of a mobile manipulator robot". In International Conference on Augmented Reality, Virtual Reality and Computer Graphics, Springer, pp. 228–245.

[404] Le, D. T., Sutjipto, S., Lai, Y., and Paul, G., 2020. "Intuitive virtual reality based control of a real-world mobile manipulator". In 2020 16th International Conference on Control, Automation, Robotics and Vision (ICARCV), IEEE, pp. 767–772.

[405] Sanford, J., Ranatunga, I., and Popa, D., 2013. "Physical human-robot interaction with a mobile manipulator through pressure sensitive robot skin". In Proceedings of the 6th International Conference on Pervasive Technologies Related to Assistive Environments, pp. 1–6.

[406] Dean-Leon, E., Pierce, B., Bergner, F., Mittendorfer, P., Ramirez-Amaro, K., Burger, W., and Cheng, G., 2017. "Tomm: Tactile omnidirectional mobile manipulator". In 2017 IEEE International Conference on Robotics and Automation (ICRA), IEEE, pp. 2441–2447.

[407] Le, A. V., Ramalingam, B., Gómez, B. F., Mohan, R. E., Minh, T. H. Q., and Sivanantham, V., 2021. "Social density monitoring toward selective cleaning by human support robot with 3d based perception system". *IEEE Access,* **9**, pp. 41407–41416.

[408] Huang, J., and Cakmak, M., 2017. "Code3: A system for end-to-end programming of mobile manipulator robots for novices and experts". In 2017 12th ACM/IEEE International Conference on Human-Robot Interaction (HRI, IEEE, pp. 453–462.

[409] Schou, C., Damgaard, J. S., Bøgh, S., and Madsen, O., 2013. "Human-robot interface for instructing industrial tasks using kinesthetic teaching". In IEEE ISR 2013, IEEE, pp. 1–6.

[410] Fernandez, V., Balaguer, C., Blanco, D., and Salichs, M. A., 2001. "Active human-mobile manipulator cooperation through intention recognition". In Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation (Cat. No. 01CH37164), Vol. 3, IEEE, pp. 2668–2673.

[411] Kim, S., Shukla, A., and Billard, A., 2014. "Catching objects in flight". *IEEE Transactions on Robotics,* **30**(5), pp. 1049–1065.

[412] Stilli, A., Grattarola, L., Feldmann, H., Wurdemann, H. A., and Althoefer, K., 2017. "Variable stiffness link (vsl): Toward inherently safe robotic manipulators". In 2017 IEEE International Conference on Robotics and Automation (ICRA), IEEE, pp. 4971–4976.

[413] Lacevic, B., and Rocco, P., 2010. "Towards a complete safe path planning for robotic manipulators". In 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, pp. 5366–5371.

[414] Chawda, V., and Niemeyer, G., 2017. "Toward torque control of a kuka lbr iiwa for physical human-robot interaction". In 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, pp. 6387–6392.

[415] Chung, W., Kim, S., Choi, M., Choi, J., Kim, H., Moon, C.-b., and Song, J.-B., 2009. "Safe navigation of a mobile robot considering visibility of environment". *IEEE Transactions on Industrial Electronics,* **56**(10), pp. 3941–3950.

[416] Reardon, C., Tan, H., Kannan, B., and DeRose, L., 2015. "Towards safe robot-human collaboration systems using human pose detection". In 2015 IEEE International Conference on Technologies for Practical Robot Applications (TePRA), IEEE, pp. 1–6.

[417] Takahashi, M., Suzuki, T., Cinquegrani, F., Sorbello, R., and Pagello, E., 2009. "A mobile robot for transport applications in hospital domain with safe human detection algorithm". In 2009 IEEE International Conference on Robotics and Biomimetics (ROBIO), IEEE, pp. 1543–1548.

[418] Marvel, J., and Bostelman, R., 2013. "Towards mobile manipulator safety standards". In 2013 IEEE International Symposium on Robotic and Sensors Environments (ROSE), IEEE, pp. 31–36.

[419] Dorabot: Ai-powered robotic solutions provider for logistics and beyond. `https://www.dorabot.com/`.

[420] Clearpath: Mobile robots for research & development. `https://clearpathrobotics.com/`.

[421] Industrial automation: Omron, europe. `https://industrial.omron.eu/en/home`.

[422] Hvilshøj, M., and Bøgh, S., 2011. ""little helper" - an autonomous industrial mobile manipulator concept". *International Journal of Advanced Robotic Systems,* **8**(2), June.

[423] Arad, B., Balendonck, J., Barth, R., Ben-Shahar, O.,

Edan, Y., Hellström, T., Hemming, J., Kurtser, P., Ringdahl, O., Tielen, T., and van Tuijl, B., 2020. “Development of a sweet pepper harvesting robot”. *Journal of Field Robotics,* **37**(6), Sept.
[424] Yanmar smash robot for a sustainable farming future. https://www.yanmar.com/global/.
[425] Robots to rescue wounded on battlefield. https://www.army.mil/article/48456/robots_to_rescue_wounded_on_battlefield.

A Appendix

Table 1. Citations for Figure. 3 (Row-by-Row L-R)

Application	**Examples**
1. Transportation	a. The AutOTrans [46], b. ADAMMS [49], c. A bi-manual variant [74]
2. Warehouse Tasks	a. Dorabot [419], b. Clearpath Robotics [420], c. OmniRob [51]
3. Machine Tending	a. ADAMMS [49], b. Omron [421], c. Little Helper [422]
4. Assembly and Additive manufacturing	a. Brick Assembly [109], b. IkeaBot [110]
5. Household and Hospital Assistance	a. El-E Assistive Robot [142], b. PR2 robot and Autobed [134], c. Human handover tasks [139]
6. Inspection and Disinfection	a. ADAMMS-UV [269], b. XDBot by NTU Singapore, c. Automated inspection [173]
7. Agriculture and Outdoor Operations	a. SWEEPER [423], b. SMASH [424], c. BEAR soldier rescue bot [425]