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# Challenges and Solutions for Autonomous Robotic Mobile Manipulation for Outdoor Sample Collection

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**Abstract:** In refinery, petrochemical, and chemical plants, process technicians collect uncontaminated samples to be analyzed in the quality control laboratory all time and all weather. This traditionally manual operation not only exposes the process technicians to hazardous chemicals, but also imposes an economical burden on the management. The recent development in mobile manipulation provides an opportunity to fully automate the operation of sample collection. This paper reviewed the various challenges in sample collection in terms of navigation of the mobile platform and manipulation of the robotic arm from four aspects, namely mobile robot positioning/attitude using global navigation satellite system (GNSS), vision-based navigation and visual servoing, robotic manipulation, mobile robot path planning and control. This paper further proposed solutions to these challenges and pointed the main direction of development in mobile manipulation.

**Keywords:** Mobile Manipulation, Autonomous, Sample Collection, GNSS, Vision, Navigation, Servoing, Path Planning, Control, Robot

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## 1. Introduction

Sample collection is crucial to plant performance, and this practice is widely used in refinery, petrochemical and chemical plants to monitor and confirm unit operation. Process technicians are responsible for collecting uncontaminated samples that are representative of the process stream, properly labelling the samples, and taking them to the quality control laboratory to be analysed. Process technicians working a 12-hour shift may collect samples four different times during their shift.

The traditional manual sample collection causes several problems. First, process technicians expose themselves to a variety of chemical and safety hazards when collecting samples. For example, the sample may contain harmful chemical (e.g. caustic liquid used in alumina processing) or the plant vicinity may have operating machineries, etc. Second, the operation is costly. Sample collection in general occurs 24 hours a day seven days a week. A team of process technicians has to be maintained and managed for this purpose. Third, it is error-prone. Some special chemicals have to be added to certain samples to stabilize the samples. Process technicians

sometimes forget adding the correct chemicals to the right samples when they perform this tedious task.

Traditionally robotic arms are fixed in structured work cells and perform 4D tasks, namely dumb, dangerous, dull, and dirty. The maturity of mobile robot technology in recent years provides an opportunity for robotic arms to perform a wide range of tasks that require both locomotion and manipulation abilities. A universally accepted term, mobile manipulation, is used to describe the tasks performed by a mobile manipulator consisting of a robotic arm and a mobile platform.

Mobile manipulation is the ideal solution to the problems of sample collection. It eliminates the hazards exposed to personnel in the plant, and it is cost-effective considering the high labour cost in the developed countries. Further, pre-programmed procedures greatly reduce the chances of chemicals being added to wrong containers.

In the 1980s, mobile manipulation started to attract the attention of manufacturing industry, and several research prototypes were developed for a variety of purposes: delivering and handling tools and work pieces, performing simple assembly tasks, and operating in hazardous environments, [1, 2]. However, the real world application of

these robots was hindered by the lack of adequate sensing technology and processing power.

In the 1990s, the application of mobile manipulation went beyond the structured industrial environments and made its way into less structured human environments. Khatib and his colleagues developed the Stanford Robotic Platform consisting of an omni-directional base and a Puma 560 robotic arm, an upper sonarring, and a lower sonar ring. This platform served as robotic assistants that were capable of obstacle avoidance in locomotion, vehicle-arm coordination in manipulation, and decentralized cooperation of multiple mobile manipulators [3-8]. Other works examined vehicle-arm coordination in terms of reactive control, motion planning, and human-robot interface [9-13].

In industry environments, efforts were put into increased reliability by error avoidance and error recovery. A combination of ultrasonic ranger sensors, laser sensors, and stereo cameras were used to ensure the reliability of navigation. Mobile manipulation was applied to move between several workstations, locate assembly parts, and perform assembly tasks autonomously[14].

Since 2000, the advance of autonomous navigation technology for example SLAM (simultaneous localization and mapping)[15] combined with the advance of sensing technology for example Lidar (light detection and ranging) brought a boom to mobile manipulation. Mobile manipulators have been used in home and healthcare [16-19], space [20, 21], and industry [22, 23].

Dynamic environments where obstacles are unpredictable and moving have been the focus of many works [23-27]. The combination of task and motion planning were dealt with by probability robotics and optimization approach [28-30]. Novel human-robot interfaces such as virtual button activated by pointing an off-the-shelf green laser pointer were proposed [31].

However, the majority of the existing mobile manipulators were designed to perform tasks in indoor environments under well-controlled lightening conditions. However, mobile manipulators for sample collection will have to travel from the lab to the plant via a shared path with pedestrians and other vehicles and performing sample collection under natural lighting conditions regardless day time and night time. This full-weather all-time operation poses substantial challenges to the current technology of mobile manipulation.

This paper is to discuss these various challenges faced by mobile manipulation for sample collection in industrial environments in terms of control and path planning, localization, visual-based navigation and visual servoing, and robotic manipulation.

## 2. Application Requirements of Autonomous Robotic Manipulation for Outdoor Sample Collection

The application requirements for robotics can be classified into 12 areas: sustainability, configuration, adaptation,

autonomy, positioning, manipulation and grasping, robot-robot interaction, human-robot interaction, process quality, and physical properties [32].

In a typical refinery as in Fig. 1, the lab and the processing plant are connected via a path shared by pedestrians and vehicles, and a number of valves are evenly distributed in the processing plant. One sample from each of the six valves needs to be collected at an interval of six hours seven days a week.

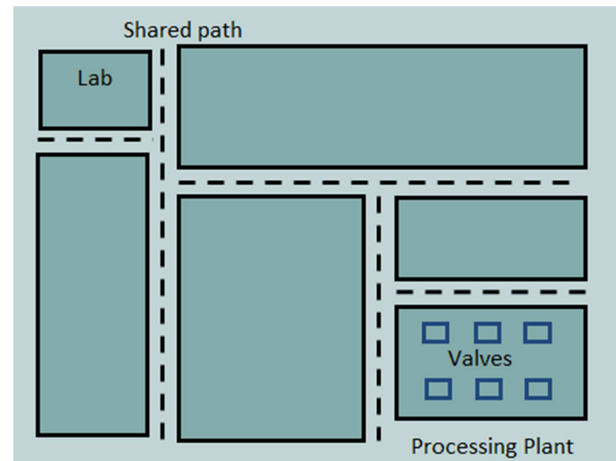


Figure 1. A typical floor plan of a refinery.

We propose to automate this operation of sample collection using a mobile manipulator consisting of a mobile base and an industrial robotic arm. The mobile base is equipped with GNSS (Global Navigation Satellite System) for localization and Lidar for path planning and obstacle avoidance. The robotic arm equipped with a stereo computer camera performs the manipulation task after the platform reaches the processing plant: Pick-up a jar from a basket, remove the lid of the jar, put the jar under the valve, switch on the valve, switch off the valve after liquid sample fills in the jar, screw back the lid, and put the jar on the basket.

Sample collection is a typical application of mobile manipulation in industrial environments, where robustness and error recovery under sensory variation, noise, and clutter are of paramount importance for a successful implementation.

Next we shall discuss the challenges faced by control and path planning, GNSS, Lidar and stereo computer vision, and manipulation and propose our solutions.

## 3. Challenges and Solutions for Autonomous Sample Collection

### 3.1. Mobile Robot Positioning/Attitude Using GNSS

#### 3.1.1. Proliferation of Satellite Navigation Technologies

GNSS utilizes global navigation satellite systems for precise positioning and navigation, and it can solve real-world problems in various applications including positioning and navigation of moving platforms in land, sea, air, and space [33-35]. Next to the familiar and widely used Global

Positioning System (GPS) of the United States of America, new and modern GNSSs are currently becoming operational, like BeiDou from China, Galileo from Europe, and Glonass-K from Russia [36, 37]. Moreover, these global systems will be joined with new regional navigation satellite systems from Japan (QZSS) and India (IRNSS), thus leading to a system of systems consisting of more than one hundred satellites. This proliferation of satellite navigation technologies will fundamentally change the positioning and navigation landscape, thus allowing for the development of exciting and challenging new applications [38, 39]. The integration of systems and the inclusion of more tracked satellites will enable robustification and improvement of the availability, reliability and accuracy of the robotic navigation solutions, in particular under constrained environments such as urban canyons [40] and open-pits [41].

### 3.1.2. Array-Based, Multi-GNSS Carrier-Phase Platform Navigator

In this project, these challenges will be met by developing an array-based, multi-GNSS carrier-phase platform navigator for the fetching robotic vehicle regardless of weather and time, thus facilitating continuous operation of the vehicle.

The proposed navigation system will consist of an array of GNSS antennas rigidly mounted to the robotic vehicle and a single reference station on top of a nearby building (Figure 2).

First, attitude (orientation) of the vehicle is determined using the Multi-variate Constrained Least-squares AMBIGUITY Decorrelation Adjustment (MC-LAMBDA) method utilizing known body frame geometry [42]. Non-linear constraints due to known antenna geometry effectively enhance carrier phase ambiguity resolution enabling instantaneous precise attitude determination. Further constraints due to the fact that the vehicle maintains levelled frame will be explored further strengthening the underlying attitude model. These constraints are further utilized using the array-aided approach for improving the positioning of the vehicle with respect to the reference station [43, 44].

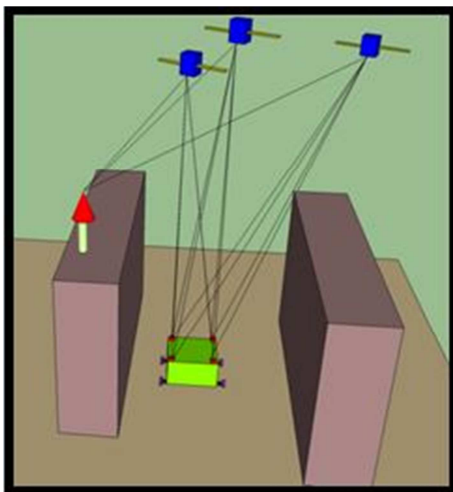


Figure 2. Navigation System for the fetching robotic vehicle.

As the robotic vehicle is proposed to travel along a path

surrounded by buildings and other structures (Figure 1), the satellite visibility will be hampered by masking effects of the surrounding structures. Making use of the location, the project will explore next generation multi-GNSS for navigation and positioning of the robotic vehicle. The Asia-Pacific region becomes the world testbed for new generation GNSS due to the developments of the Chinese BeiDou, and the Japanese QZSS, and the Indian IRNSS. The number of satellites is expected to increase much faster in this region than in any other area of the world (Figure 3).

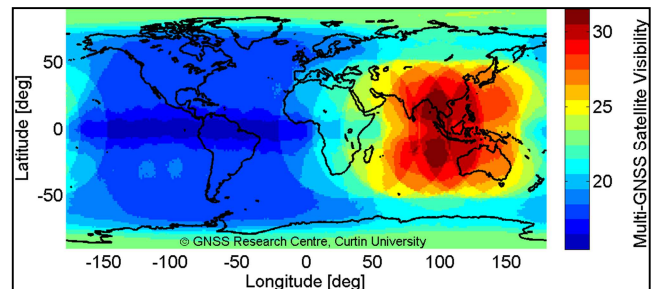


Figure 3. Global satellite visibility for GNSS/RNSS.

Integration of multi-GNSS data [37, 44, 45] will enhance reliability and availability of navigation solution in satellite deprived environment (Figure 2).

### 3.2. Vision-Based Navigation and Visual Servoing

#### 3.2.1. Lack of Robust and Cheap Navigation Sensors

One of the key factors that have impeded the greater adoption of autonomous mobile robots is the lack of robust and cheap navigation sensors. Computer vision technology has made significant progress over the last decade that it is now becoming possible for camera to perform a range of different physical measurements (i.e. ranging, 3D reconstruction and etc.) that were traditionally done with specialised high cost sensors (i.e. laser scanner, sonar and etc.). These vision-based systems analyse the sequence of images taken from the outdoor scene from the camera/s attached to the vehicle platform and extracting the visual cues which are the used to plan the action of the vehicle [46]. The actual camera system used depends on the purpose; camera can be monocular, multi-view and omnidirectional to meet various needs.

In recent years, much attention is being devoted to solve the problems of translating the visual information obtained from camera for navigating a vehicle autonomously through the environment [47]. To do this requires the determination of (1) the 3D scene geometry, and (2) the camera orientation with respect to the scene. Multi-view stereo is an established technique used to recover the 3D surface profile of the scene. It relies on capturing multiple views of the scene to provide the depth disparity needed to construct the 3D scene geometry [48].

#### 3.2.2. Structure from Motion Techniques and Visual Simultaneous Localisation and Mapping

Advances in Structure from Motion techniques which generate 3D scene from image sequences provide the advantage of lower hardware cost suitable for navigating

autonomous platforms. Visual SLAM (Simultaneous Localisation and Mapping) techniques provide the added benefit of estimating the location of the platform in addition to performing the mapping function. The robustness of VSLAM techniques have improved significantly and this technique has been implemented in many navigation systems both indoors and outdoors [49]. VSLAM has also been used in mobile devices in the form of applications to deliver augmented reality experiences to consumers. In the area of robotic manipulation, visual servoing techniques are commonly adopted to provide a visual feedback as the manipulation follows a sequence of predetermined paths [50]. The camera can either be attached to the robotic hand (i.e. Eye-in-Hand) or fixed to the world away from the hand (Hand to Eye). This is ideal for scenarios where accurate feedback of the robotic actuator is needed for say opening a valve or the lid of the sample collection jar.

### 3.3. Robotic Manipulation

#### 3.3.1. Uncertainties in Manipulation

Currently and in the foreseeable future, robotic arms will have to perform tasks [51] using uncertain, even piecemeal views of the world due to the limitation of the sensor and actuation technologies. Increasing the accuracy of robots required for fine-manipulation [52-57] in industrial environments is expensive and ultimately stifling.

Uncertainties may be caused by robot positioning errors and vision systems that can only provide piecemeal views of the world due to low resolution and/or occlusion. As a result, the uncertainties could exceed the accuracy required by sample collection tasks. Complex manipulation tasks under uncertainties have to be performed using multiple sensors such as vision and force/torque, tactile, and distance sensors to increase the robustness.

Uncertainties in manipulation have been coped with from different perspectives. Su and Lee [58] developed the propagation of uncertainty before and after a primitive action to integrate the uncertainty information into a task plan that consisted of a sequence of primitive actions. Li and Payandeh [59] design the forces exerted on the object by agents with which the object can follow a given trajectory in spite of the uncertainty on pressure distribution. Hsiao, Kaelbling and Lozano-Perez [60] provided a method for planning under uncertainty for robotic manipulation by partitioning the configuration space into a set of regions that were closed under compliant motions. Berenson, Srinivasa and Kuffner [61] present an efficient approach to generating paths for a robotic manipulator that are collision-free and guaranteed to meet task specifications despite pose uncertainty. Stulp et al [62] presented a simplified version of a model-free reinforcement learning algorithm to simultaneously learn shape parameters and goal parameters of motion primitives and use shape and goal learning to acquire motion primitives that were robust to object pose uncertainty.

In sample collection, the uncertainties mainly come from the positioning errors of the mobile base and the errors of object pose identification of the computer vision system. We

propose to use guarded moves [63], in which a robot reduces the uncertainty by accomplishing relative motion and/or controlled dynamic interaction between the end-effector and the objects.

#### 3.3.2. Automatic Generation of Guarded Moves

Automatic generation of guarded moves has been studied from the point of view of assembly tasks. Lozano-Perez, Mason and Taylor [64] presented the synthesis of compliant motion strategies from geometric description of assembly operations and explicit estimates of errors in sensing and control. Donald [65] presented a formal framework for computing motion strategies in the presence of uncertainties arising from sensing errors, control errors, and uncertainty in the geometric models of the environment and of the robot. Xiao and Zhang [66] developed a general geometric simulator allowing flexible design of task environments and modelling of nominal and uncertainty parameters to run the algorithms and simulating the kinematic robot motions guided by the replanning algorithms in the presence of uncertainties. LaValle and Hutchinson [67] developed a general framework for determining sensor-based robot plans by blending ideas from stochastic optimal control and dynamic game theory with traditional preimage backchaining concepts.

For the sample collection in a refinery, the key steps in robotic manipulation include putting a jar under a tap, switching on a valve, and switching it off after liquid sample filling the jar. These operations need accurate positioning. Hence it is indispensable for the robotic arm to cope with the uncertainties arising from the positioning/attitude errors of the mobile base and the errors of object identification of the computer vision system. Guarded moves provide very precise information about the relative poses of robotic arm and environment, thus are essential to mobile manipulation in a refinery.

### 3.4. Mobile Robot Path Planning and Control

#### 3.4.1. Path Following of Holonomic and Nonholonomic Mobile Platforms

As discussed in Section 1, the autonomous mobile manipulator consists of a manipulator mounted on a mobile platform. It combines the dextrous manipulation capability offered by fixed-base manipulators and the mobility offered by mobile platforms. However, the mobile manipulator brings about a number of challenging problems in path-planning and control. The following fundamental issues need to be addressed for carrying out tasks of the proposed mobile manipulators:

(i) How can we plan the effective motion trajectory of a mobile manipulator under both holonomic and nonholonomic constraints?

(ii) How do we design the hybrid motion/force control and hybrid position/force for the mobile manipulator since it needs to interact with the environments including collision avoidance, carrying out operations at valve locations, recharge batteries, and so on?

A wheeled mobile manipulator is fundamentally an

underactuated system subject to nonholonomic constraints. A combination of a wheeled robot and a multi-link manipulator also creates kinematic redundancy. Moreover, the wheeled robot and the manipulator dynamically interact with each other. In addition, the environment contains both stationary and moving obstacles. A good survey of the recent development in terms of nonholonomic motion planning is given by Li and Canny [68]. There are many studies on motion planning of mobile robots using various approaches, e.g., potential field [69], graph search algorithms [70], the A\* algorithm [71], Bellman-Ford algorithms [72], the wavefront algorithm [73], and visibility graph approaches [74]. For the motion generation plan planning for mobile manipulators, since mobility is the main concern, the approaches are similar to motion planning for mobile robots. However, the problem is to choose/derive an appropriate path-planning method so that it can be incorporated in a design of the motion control system.

The mobile manipulator needs to park at valve, sample returning, and battery recharging locations, and to move along the planned-path. Thus, we need to solve the control problems consisting of fixed-point stabilization, and [75-79]; trajectory-tracking, which deals with the design of controllers that force a mobile robot to reach and follow a time parameterized reference trajectory (i.e., a geometric path with an associated timing law) [78-85]; or path-following, in which the robot is required to converge to and follow a reference path that is specified without a temporal law (i.e., dealing with the design of controllers driving the robot's trajectories to a maneuver up to time re-parameterization) [75, 86-98]. The path-following task is more suitable for the proposed mobile manipulator since it can use the path-derivative as an additional control input (giving more robustness) and the sample collection time is not so strict.

Existing solutions to path-following control of mobile robots can be roughly classified into four main methods. In the first method referred to as the Serret-Frenet one, the Serret-Frenet frame is used to define the path-following errors, i.e., the cross-track and heading angle errors, then the control inputs (velocities when only kinematics is considered or torques applied to the driving wheels of the robot when both kinematics and dynamics are considered) are designed to stabilize these errors at the origin (e.g., [75, 86, 87]). Due to singularity in the cross-track error dynamics, this approach requires the robot's position to be within a tube, of which the center-line is the path and the radius is less than inverse of the path's curvature, i.e., only local results are obtained for curved paths. To resolve the singularity, a combination of the trajectory-tracking and path-following using the Serret-Frenet approach in the sense that the lateral path-following error is not always set to zero (to avoid singularity in the cross-track error dynamics) and that the path-parameter is used as an additional input to control the lateral path-following error. Thus, global control results are usually obtained. Exemplary works includes [88-90].

The second method defines the path-following objective as the one of forcing a robot to follow a virtual robot moving on the reference path (e.g., [91-93] and [94], Chapter 14, Section

14.1.4). Polar coordinates are used to interpret the path-following errors, i.e., the distance and angle between the real and virtual robots. Roughly speaking, the approach is to steer the robot such that it heads toward the virtual robot and eliminates the distance between itself and the virtual robot. This approach requires the robot not to be too close to the path to avoid singularity due to the polar coordinate representation.

The third method is referred to as the transverse feedback linearization (TFL) method [96-98] (see also [99] for an extension to N-trailer robots, and [100] for a consideration of PVTOL aircraft). This method involves with conversion of the path-following problem to an input-output feedback linearization problem (cascaded with a zero dynamics problem) with respect to an appropriate output, which usually defines the reference path. In this context, the TFL method is related to the differential flatness approach [101]. This method usually achieves local results.

The fourth method referred to as the level curve one has been recently introduced in [95] (see also [102] for an extension to a three dimensional path-following problem) for design of a path-following controller for unicycle-type mobile robot. This method is based on the observation: if the position of the robot satisfies the equation of the reference path, then the robot must be on the path. Thus, similar to the TFL method neither distance from the robot to the reference path nor virtual moving robot is needed. Although it is related to the TFL method, there is a vital difference between these two methods. The suitable output is differentiated till the control inputs appear in the TFL method while the level curve method directly control this output. This difference can be understood as the difference between the feedback linearization control design [103] (Chapter 13) and the backstepping method [104] (Chapter 2). The level curve method is also used to design a global path-following controller for underactuated ships in [105]. An initial work in this approach for global path-following control of mobile robot is given in [106].

### 3.4.2. Integrated Approach to Path Planning

Path-planning: The floor and structure maps from the operational office, and various curve fitting algorithms are used to generate a preplanned-path. Valves, sample returning, and batteries recharging locations are marked on this preplanned-path. The preplanned-path is served as a preliminary path for the mobile manipulator to follow and to park at the above locations. The preplanned-path is then on-line deformed if necessary for unforeseen stationary or moving obstacles by an algorithm embedded in the mobile robot motion control system.

Mobile robot motion control: The positioning (GNSS, computer vision, and local sensing devices: ultrasonic, infrared, etc.) and manipulator-health information is used for the mobile robot motion control design. The artificial potential field is incorporated into the level curve motion control approach for both mobile robot motion control and obstacle avoidance. The initial work in [106, 107] is to be further explored in conjunction with [79] for a design of a mobile robot motion control system that can perform both

stabilization (parking) and path-following objectives.

Robot manipulator control: Information from the manipulator-health, and location activity are used to activate this control. When the mobile manipulator is parked at a desired location, a signal string is sent to the robot manipulator to activate a preprogramed software embedded in the manipulator for valve or sample returning or battery recharging operations.

## 4. Conclusion

This paper reviewed the challenges faced by robotic manipulation for sample collection and proposed solutions to these challenges. Mobile robot would explore next generation multi-GNSS for navigation and positioning / attitude of the robotic vehicle. Vision-based navigation and servoing would use the advances in structure from motion (SfM) techniques which generate 3D scene from image sequences. Robotic manipulation would make use of guarded moves to reduce uncertainties in unstructured environments. Mobile robot path planning and control would integrate the artificial potential field into the level curve motion control approach for both mobile robot motion control and obstacle avoidance. These proposed solutions pointed a road to a successful implementation of mobile manipulation for sample collection.

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