1 Introduction

1.1 Background

Modern industrial activities rely intensively on advanced robotic automation technology since robots exhibit better accuracy, repeatability and endurance than human in many production tasks, and they are becoming more and more economical compared with human resources. The annual installations of industrial robots in various areas has been steadily growing in the past decade [1, 2]. Besides traditional industrial applications, service robots are currently also coming into the spotlight. Instead of manufacturing goods, these newly defined robots benefit from the development of artificial intelligence to provide professional services in a generally more cognitive and interactive manner. A technical report [3] by the Joint Research Centre of European Commission has revealed that a considerable quantity of organisations in Europe are already employing service robots mainly in warehouse management systems, assembly works, cleaning or waste disposal, etc. The majority of them as well as an increasing portion of industrial robots involves the close co-existence and cooperation with humans, in which context the robot is often phrased as "cobot", and they are desired to display enhanced safety, intelligence and responsiveness during operation.

The demand of production and service using multiple networked cooperative robots [4, 5] has become higher due to increased complexity of the task and working environment of robots, as well as the flexibility of multi-robot systems, where the cooperating robots can either team up for a single heavy-load assignment or split into individual agents to work efficiently in parallel. On one hand, multi-robot applications include cooperative exploration and mapping, robotic rescue [6] and surveillance [7, 8], formation control [9, 10] (e.g. vehicle fleet [11] and live drone performance [12]), etc., where the cooperating robots are not physically connected to each other and only motion performance is of importance. On the other hand, applications such as object transportation, cooperative manipulation and assembling impose physical coupling inside the multi-robot system. Cooperative transportation refers to moving a single object towards a desired pose, namely both position and orientation, with a robot team that has a larger overall maximum payload than individual robots [13]. This can be achieved by implementing formation control on mobile platforms that support the load from underneath [14] or cage and push the workpiece [15, 16]. In recent years several aerial cooperative transportation systems using unmanned aerial vehicles are also developed [17, 18, 19]. Multi-robot manipulation can be very similar to transportation, except that the desired object motion usually has a higher Degree Of Freedom (DOF) and complexity, making agile robot arms a necessary component of the system [20, 21]. In addition to the improved payload capability, the system is also more efficient in the sense that depending on the demand, the robots can either team up for a large common task or work separately on individual smaller tasks. Moreover, a multi-arm manipulation system can agilely handle soft objects [22], for example as in cloth folding [23, 24] and string knotting [25]. Assembling is another common task for multiple manipulators [26, 27, 28]. Different from transportation and manipulation, the inter-robot physical interaction does not exist consistently, but only during contact.

The scope of this dissertation is on the cooperative manipulation of a jointly grasped rigid object using several high DOF robot arms. Its practical applications are for example flexible transportation and the handling of tools that require multiple grips such as steering wheels and big round valve handles. The benefit of this technology is widely recognised, and many multi-arm rigs have already been built, including fixed based platforms [29], mobile manipulators [21], and humanoid robots like *Rollin' Justin* [30] and *Atlas* [31]. Commercial products also exist, among which *YuMi* [32] and *WorkSense W-01* [33] are the most famous. The development of advanced dual-arm robot systems is even included in the recent national research and development program of China [34]. Meanwhile, with cobots being progressively welcomed, these multi-robot systems are also desired to safely and intelligently interact with human in both industrial and service scenarios under complex constraints in the daily environments [35, 36], and this has given rise to the "robot society" concept [37, 38] that eventually induces a large-scale multi-human-multi-robot system with high dimension, complexity and communication uncertainties. The networked and coordinated control for multi-robot manipulation in this context with the aforementioned safety and responsiveness requirement in consideration remains an important but challenging problem nowadays.

Transporting the workpiece to a desired pose is the primary objective for cooperative manipulation, but in an uncertain environment the robots have to keep sensing their surroundings and avoid dynamic obstacles (e.g. humans) at the same time. Considering the installation conditions and the overall size of the robot team, this is often difficult to accomplish with a fixed formation. Instead, the redundancy of the system should be utilised to achieve flexible whole-body collision avoidance while minimising transportation error. However the rigid physical connection due to grasping the single object makes this much less straightforward, because it implicitly transfers the internal joint-space constraints (e.g. mechanical joint limits, manipulability, maximum joint torques) of all agents to each other, which normally reduces the overall motion capability of the group. For example, when one robot attempts to move the workpiece to avoid an unexpected obstacle, another robot may already have reached its joint limit or singularity and cannot move further. The rigid grasping enforces obedience of this local constraint by all robots, making the desired avoidance motion infeasible. Therefore, it is necessary to maximise the internal joint-space performance of the manipulators online so that they are well-prepared for abrupt changes in the dynamic environment. Furthermore, since each robot usually has a limited field of view of the environment, obstacles could cause different motion intentions by the cooperating members. This temporary incoordination is acceptable for soft inter-robot connection, but with rigid physical coupling it can lead to large and dangerous conflicting forces on the workpiece and end effectors. The continuous guarantee of motion coordination and internal force suppression, together with the aforementioned object transportation, whole-body obstacle avoidance and internal performance optimisation, are thus key issues to tackle in a multi-robot manipulation system, and the solution to them through intelligent autonomous control technology will be the ultimate topic of this dissertation.

1.2 Related Work

Robotic cooperative manipulation could be achieved with pure mobile platforms when only planar motion is desired. But these systems cannot move the object in a higher dimension, therefore the ability of 6-DOF trajectory tracking and complex obstacle avoidance is quite limited. Additionally, due to the direct contact between the mobile robots and workpiece, it is difficult to model the physical coupling and control inter-robot dynamic interaction. The adoption of dexterous robot arms and grippers can solve this problem. With this setup, [39] first formulated the kinematic and dynamic model of the system, and [40] proposed a virtual linkage model to analyse the internal forces on a jointly grasped object. A summary of the early research can be found in [41]. Based on these results, [42] and [43] have revisited the detailed dynamics of multi-arm cooperative manipulation systems under impedance control and revealed the explicit relationship between local robot control forces and the actual strains at the grasping points. Besides, they have also demonstrated conditional stability and passivity of the system. These works have nicely established the foundation for cooperative control design.

Several early researches on the control of multi-robot manipulation systems existed already in the 1990s. In [44] an augmented object model is created around the grasped workpiece as a basis for cooperative manipulation control design. [45] developed a nonlinear feedback control for a dual-arm robot system, where not only the pose but also the interaction forces are formulated in the system output. The control of cooperative manipulators on a space satellite is discussed in [46]. In [47] a learning-based control is presented to address the parametric uncertainty in the multi-robot manipulation system. These works have modelled and controlled the cooperative robot group from a centralised point of view, and this control structure is nowadays still widely used on dual-arm systems. For example, [20] introduces a centralised impedance control framework focusing ultimately at the dynamics of the manipulated object. A motion planning method based on the Inverse Kinematics (IK) of the overall system is developed in [35]. Inverse Dynamics (ID) method is also extended to multi-robot systems as in [48], where a centralised ID controller generates motion task torques as well as an internal torque component to maintain the frictional hold on the workpiece. Some approaches like asymmetric and symmetric bimanual control are specifically designed for dual-arm systems. In [49] this technique is combined with compliant movement primitives to steadily maintain the gripper formation under force disturbances at arbitrary points on the robot body. Although less often, the application of centralised control strategy on larger-scale systems has also been studied. In [29] a manipulation platform consisting of four redundant manipulators are modelled as a robotic hand, and grasping control techniques are utilised to accomplish the desired motion of the object and maintain contact forces.

Decentralised control is another option for multi-robot systems. In this type of control there is no central processing unit that acquires all data from the group and generate control input for all members. In contrast, the control is decomposed and each robot runs a part of it. The leader-follower structure is the most investigated type of decentralised cooperation strategy, where one of the cooperative agents is assigned the “leader” role, and the other robots are “followers”. The group motion decision is mainly made by the leader based on its recognition of the situation, while the followers run a local motion controller to follow that decision. Unlike pure formation control [9], in a manipulation system the physical coupling between the robots can be utilised by the followers to estimate the motion intention of the leader, thus communication is not necessary. K. Kosuge *et al.* presented a series of works [50, 51, 52, 53] about leader-follower cooperative manipulation with leader trajectory estimation based on local motion information. Since no communication is required, the method has also been extended to human-led robot groups [54, 55]. In [56] a leader-follower coordination strategy is proposed with interaction-force-based estimation. Leaderless decentralised cooperation also exists, where every robot plays the same role and contributes equally. This can be achieved by providing the desired manipulation motion *a priori* to all agents and let their local motion controllers track the trajectory in synchronisation [57]. In fact, some existing centralised methods can be trivially decomposed, such as [58]. Otherwise, a decentralised control framework with impedance control implemented on mobile manipulators is proposed in [21]. Based on this idea, [59] employed adaptive impedance coefficients to reduce internal forces under local disturbances.

Industry 4.0 has greatly motivated research activities on distributed control, which is basically decentralised but with (usually limited) communication, so that both coordinated performance and scalability are fulfilled and plug-and-play feature can be more easily realised. Some works achieve distributed cooperative manipulation by formation control and caging/pushing motion of mobile vehicles, such as in [60, 61, 62]. With the addition of robot arm manipulators, [63] has introduced a method to estimate the inertial parameters of the manipulated object in a distributed fashion. In [64] a distributed mobile manipulation control is developed to guarantee workpiece trajectory tracking while redundancy is utilised for obstacle avoidance by the mobile platforms. The approach is validated in simulation. [65] combines the distributed structure with reinforcement learning to tackle object manipulation by multiple arms. Recently S. Hirche *et al.* published [66] and [67], one of which proposes a fully distributed adaptive control for cooperative manipulation, while the other paper discusses event-triggered communication in such a system. Both works presented realistic experiments on dual- and triple-robot platforms with high-DOF arms.

In multi-objective scenarios as will be addressed by this dissertation (see Section 1.1), optimisation-based control design often suits well since multiple goals and constraints can be handled simultaneously and systematically. Abundant results on optimal trajectory planning can be found for single-arm robots [68, 69]. When extended to scalable multi-robot systems, the solution to the cooperation-oriented optimisation problem is preferably distributed as stated above. Various approaches for this purpose have been investigated but they are mostly applied to motion planning of mobile robots with additional subtasks such as collision avoidance and energy consumption minimisation, as in [70, 71, 72, 73], and a Distributed Model Predictive Control (DMPC) routing scheme is developed in [74] for a team of drones. One rare example of distributed optimisation for cooperative robot arms is [75], where the problem formulated at velocity level involves object transportation, velocity limiting and null-space obstacle avoidance, and a simulational study is shown.

The potential motion capability of robot manipulators depends on the actual joint configuration, and several criteria have been defined to mathematically describe the "quality" of a robot pose. The most studied aspects are manipulability [76, 77] and mechanical joint limit, and many research works (e.g. [78, 79, 80, 81]) optimise them at the same time to maintain the dexterity of the robot. Self-collision avoidance [82, 83] is another important concern especially for high-DOF manipulators. Some works also make use of redundancy to minimise joint torques [84, 85]. Since multi-agent cooperation performance could be bottlenecked by any individual member, the extension of some performance indices to multi-arm applications are studied. [86, 87] have shown that the common workspace of multiple robots are usually smaller than individual manipulators. The manipulability measure is extended to multi-robot systems in [88], and the optimisation of manipulability for a dual-arm system can be found in [89, 90]. A cooperative robot control subject to joint limits is presented by [91], and in [92] the avoidance of both joint limit and singularity is taken into consideration.

1.3 Motivation

It is clear that the combination of multi-robot manipulation system and the “cobot” concept, both of which are currently attracting more research interest and effort, has promising potential applications in various scenarios. However to the best knowledge of the author, no existing works have considered cooperative whole-body reactive manipulation in dynamic environments, which is an essential feature for a cobot system. Although the above literature review has acknowledged a few works for this goal, they rely solely on the motion of mobile vehicles so the flexibility of the system is restricted. Some works did implement obstacle avoidance on multi-arm systems, but the desired transportation of the workpiece is defined as hard constraint and agile whole-body avoidance is still not achieved. Another missing discussion is the online optimisation of individual internal joint-space performance for the purpose of improving cooperation quality during collision-free manipulation. When tackling all these issues in an uncertain and dynamic environment, the coordination between robots must be guaranteed to avoid dangerous internal conflicting forces, and so far this topic is only investigated in static environments. In short, a) rigid object transportation, b) whole-body collision avoidance, c) internal performance optimisation, and d) suppression of conflicting forces, have never been accomplished simultaneously.

In order to online optimise the robot pose to improve internal performance criteria, their mathematical characterisation is required. Various performance indices, e.g. joint limit and manipulability, are defined and studied in literature, but usually no more than two of them are considered or optimised at once in each piece of research, and there is no framework to systematically integrate all of them into a single control design. A comprehensive consideration for all of them during robot motion is actually important but absent. Additionally, although in a multi-robot system the individual joint-space performance becomes more critical, its influence on the cooperation outcome has sel-