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17th CIRP Conference on Modelling of Machining Operations

# Digital chain development for sanding application with a kinematically redundant robotic system

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## Abstract

Naval industries are looking for new ways to perform complex tasks on large and stationary parts. In this context, mobile manipulators which consist on a manipulator (6 Degrees of Freedom) mounted on a wheeled base (4 DoFs - Automated Guided Vehicle) are a promising solution. In this paper, such one is presented and the way to control it is explained. It appears that the redundancy management can be solved by fixing geometric parameters and adjusting timers to control the end effector. Staubli Robot and AGV are synchronised via a Main computer : the digital chain development is highlighted and ways are proposed to improve the mobile robot behavior via the redundancy management.

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**Keywords:** Mobile robot; Automated Guided Vehicle; Digital Chain ; redundancy management

## 1. Introduction

Currently, performing complex tasks on large and stationary parts in Naval Industries becomes a nightmare for musculoskeletal disorders and for improving the productivity. Mobile robot based on an Automated Guided Vehicle (AGV) seems to be well adapted and would permit to save time, get a consistent quality and free the workers to make dangerous or repetitive tasks. Mobile robot generally consists of a robot arm mounted on a wheeled base (e.g. automated guided vehicle (AGV) or mobile robot). Most of the mobile manipulator systems are designed to move the robot located on a structure inside a large workspace. Companies offers solutions such as Kuka (Kuka Moiros). Industrial environment is an important element to design a robotic architecture and efforts must be made to connect Humans to this new tool via the Human Machine Interface. In the frame of Coroma project, such a development is currently performed. Funded by the European Commission, this project stands for a COgnitively enhanced RObot for flexible MANufacturing of metal and composite parts, it aims at developing intelligent, flexible and safe Robots where mains innovations

can be brought with minimum programming effort required, an autonomous workshop navigation and a safe human - robot-machine collaboration. A lighter and flexible mobile manipulator architecture has been developed by researchers of Université de Nantes and LS2N (Laboratory of Digital Sciences of Nantes) using two commercial robots: an Automated Guided Vehicle produced by BA Systèmes (B2A) and an industrial manipulator, a Stäubli RX160L and an active compliant tools (Figure 1). This mobile manipulator has been initially used for 3D printing applications in the context of Batiprint3D project [1-2]. This project achieved the building of affordable houses using 3D printing technology. Previous work with this AGV was presented and focus on stability issues [3]. The novelty of this paper is proposing a scientific perspective on the digital chain management when a redundant robotic system is considered where an AGV and an Industrial Robot are controlled via a main computer. This paper is organized as follows : the first section presents the mobile robot developed. As a kinematically redundant system, a state of the art explains how to manage it. In our case, due to the fact the mobile robot includes two technological brick, they need to be synchronized and deep explanations are given to use them at the same time for a sanding task. The third part explains the digital chain and its use. Finally, we adress scientific perspectives to improve the redundancy management.

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Fig. 1. Mobile Robot developed to perform sanding application : it includes an Automated Guided Vehicle, An industrial Robot Staubli RX160L and an active compliant tools for sanding

## 2. Mobile Robot development

The mobile robot includes several equipments to perform sanding tasks. Each of them are detailed inside the following subsection.

### 2.1. Automated Guided Vehicle

The automated guided vehicle is mainly used for logistic activities and it includes a specific odometry. Proximity sensors are located at its base to prevent contacts with its environment. At the top of the AGV, a double laser scanner observes targets stucked on the wall to define its location and its navigation. Regarding a frame fixed to the workshop, the positioning of the AGV is defined via 3 parameters : A position on a plane  $X_{AGV}$ ,  $Y_{AGV}$  and an angle  $\theta_{AGV}$ . Its movement is produced by a wheel able to turn on itself : 2 Dofs to perform a curvilign trajectory. A lifter allows to raise the Staubli Industrial robot : a parameter  $H_{AGV}$  is considered. Inertial loads has been deeply studied on such a system in order to improve the accuracy [4]. However, we consider its influence to be minimal in the sanding application.

### 2.2. A Structure for the lifter

A structure plays the role of interface between the automated guided vehicle and the industrial robot. It includes the electrical cabinet to manage the industrial robot. Another one focuses on

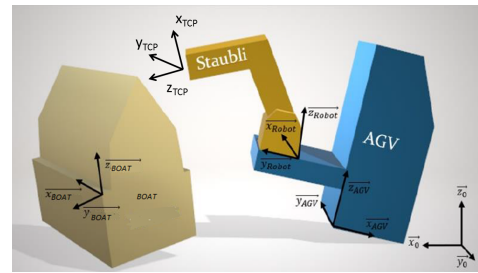


Fig. 2. Frames associated to the master (boat), AGV and Staubli

the compliant tool and we design a specific box to collect the "counterweight" to avoid tilting [3].

### 2.3. An industrial robot

The industrial robot is a Staubli RX 160 XL. This robot offers good performances in terms of workspace versus its weight. The robot has 6 Degrees of Freedom and is located at the border of the structure to have a large area on the side of the AGV.

### 2.4. Active Compliant tools

The active compliant tools for sanding is a Ferrobotics system. It allows the robot to adapt itself to suit complex surfaces, meaning it is able to automatically measure the forces that needs to be applied.

### 2.5. Control

Each system can be controled separately due to the fact they have their own control cabinet. A main computer "Beckoff" was installed to manage the data exchange between the differents system.

The use of an industrial robot (6 DoFs) to perform a sanding tasks, defined by 5 parameters generates a first-order functional redundancy to perform a machining task characterized by 5 DoFs. That means that one complementary parameter has to be taken into account to define the robot pose completely. This functional redundancy is characterized by the angle around  $\Delta$  the compliant tool. The total degree of redundancy is equal to 4 :  $q_{wheel1}$ ,  $q_{wheel2}$ ,  $H_{AGV}$  and  $\Delta$ . In order to perform the sanding task, we finally must know in real time the position of the different frames meaning frame associated to the master, the one associated to the AGV, the one associated to the industrial robot. Figure 2 details the following frame inside the frame fixed to the industrial workshop.

## 3. State of the art on redundancy management

For 50 years, scientific research proposes works to manage kinematic redundancy. Due to their serial architecture (6 joints), Industrial robots have an anisotropic behavior in their workspace and have limits of use in terms of workspace, accessibility, singularity, collisions. The increase in the number of

joints and therefore in the mobility of robots makes it possible to overcome these limitations [5-6].

The management of kinematic redundancy reveals a sub-constrained problem requiring the integration of criteria, known as optimization criteria, to improve the overall behaviour of the robotic system. The first criteria which has been introduced focused on joint stops [7] and singularity [8]. In recent years, literature proposes new optimization criteria to improve kinematic performances, mechanical performances, stiffness [9-11].

As far as kinematic redundancy management methods are concerned, they are numerous and can be classified as local one where a local point of a path can be relocated regarding optimization criteria. Global methods lead to a solution for all the point of a path but are more complicated to implement. Among the most commonly used methods are Moore Penrose's pseudo-inverse methods [12], projection on the nucleus of the Jacobian matrix [9-10], approximate methods [11] or genetic algorithms [11].

The choice of the criteria and the method is based on the process and the expected robot behavior in terms of speeds and deflection. For example, for machining applications, process is often studied and criteria based on the cantilever or deflection of the robot is used. Moreover, following the direction of the machining effort, in order to limit the deflection, the force can be oriented toward the wrist of the robot. Finally, on-line optimization is, to our knowledge, rarely used and a previous step of offline path planning is preferred to avoid any issue during the synchronization.

Based on our application, the process of sanding needs to be characterized. Literature highlights various influent parameters on this material process removal such as the force applied, the speed, the de-pinching angles, the overlap area,...[14,15]. In our case, the expected behavior is to insure the speed, the applied force and keeping the industrial robot far from the wrist singular position and the border of its workspace. This topic will be discussed in section 5.

#### 4. Application on the sanding task

This section is dedicated on the development performed to synchronize the AGV and the industrial robot. It includes a description of the data transfer between the different elements and the geometric criteria which has been chosen to manage the kinematic redundancy.

##### 4.1. Control management

As presented before, each system has its control cabinet and a main computer allows to transfer information between the AGV and the industrial robot. The AGV needs some elements to perform a trajectory. First of all, the AGV is located on a workstation it goes via a speed defined by the user from one to another : All workstation must be defined. During the trajectory, the AGV, via the laser scanner, sends its current location. We introduce various geometric transformations including :

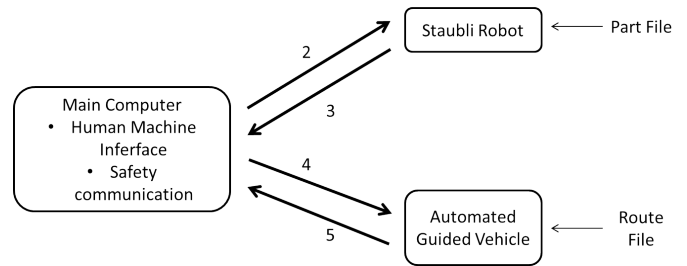


Fig. 3. Communication between the 2 control cabinet and the main computer

- $A_{MasterTCP}$  : Given by the CAD-CAM software, it gives access to the surface of the master inside the frame of the master
- $A_{WorldMaster}$  : The location of the master inside the frame of the workshop.
- $A_{WorldAGV}$  : The current position of the AGV inside the frame of the workshop
- $A_{AGVstructure}$  : The position of the structure regarding the AGV frame. This transformation takes into account the height of the structure  $H_{AGV}$
- $A_{structureTCP}$  : The positioning of the end effector (Tool Center Point) regarding the structure

The main computer gives its approval to the AGV to go to another workstation and between this two stations, sanding activity is approved. Regarding the current position of the AGV, the robot executes the trajectory. The sequence can be structures as follows (Figure 3):

- Step 1 : The user defines via the Human Interface Machine the area that the robot needs to sand (Area between two workstations)
- Step 2 : The main computer gives the height positioning of the forks  $H_{AGV}$ , where the AGV must go and the speeds between.
- Step 3 : The AGV sends its positioning in real time ( $X_{AGV}$ ,  $Y_{AGV}$ ,  $\theta_{AGV}$ )
- Step 4 : The main computer gives the positioning of the AGV and the control cabinet of the industrial robot calculates its "little" displacement, always no null.
- Step 5 : The Staubli performs its trajectory and send a message to the main computer

In the case of the AGV is stopped due to the presence of a worker, the robot leaves its trajectory and saves the position. Once, the AGV is ready, the sanding task restarts. In the frame of Coroma Project, a technological "brick" is currently developed to have a better understanding of the environment.

In this first implementation, several simplifications were performed. The functional redundancy is not considered and CAD-CAM software sends back 6 parameters (3 positions and 3 orientations) to define the surface to sand. To solve the kinematic redundancy, in a first approach, it has been chosen to project the path of sanding on the line of displacement of the AGV (Figure 4). In this way, this allows the AGV path to be fully constrained.

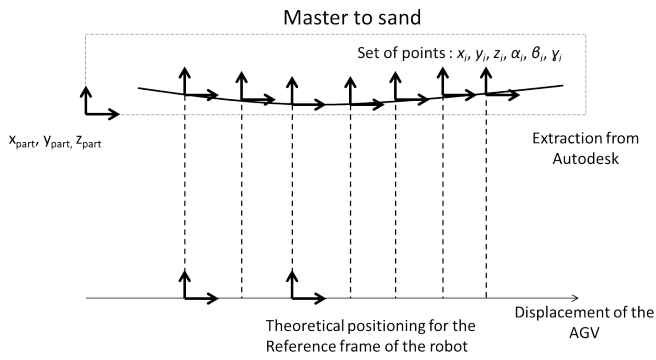


Fig. 4. Geometrical criteria : projection of the path to sand on the displacement of the AGV

The calculation is done offline inside the CAD-CAM software. One element must be solved : the case where the industrial robot reach th Concerning the industrial robot, a specific calculation, in real time, is done to avoid it having a no null speed (the robot must always move). In this way, 2 files are generated : one for the Staubli robot which will take into account the Height of the structure  $H_{AGV}$ , the current position of the AGV inside the workshop, the calibration of the master inside the workshop. The second one for the AGV is a calculation from the part file generated inside the CAD-CAM software which takes into account the geometrical criteria. To manage the robot trajectory, the calculation performed by the Staubli control cabinet in real time is a new matrix  $A_{StructureTCP}$  equal to :

$$A_{StructureTCP} = A_{AGVStructure}^{-1} * A_{WorldAGV}^{-1} * A_{WorldMaster}^{-1} * A_{MasterTCP} \quad (1)$$

#### 4.2. Implementation on the mobile robot

##### 4.2.1. Identification of the master and the TCP

Two identification are performed before trial on the part (Figure 5). The first one is dedicated to the TCP in the frame of the AGV  $A_{AGVTCP}$ . The objective is taking various points around a point. This method is the most widely used. Then, the identification of the master can be done meaning the characterization of the transformation matrix  $A_{WorldMaster}$  which is the combination of  $A_{WorldAGV}$ ,  $A_{AGVTCP}$  and  $A_{TCPMaster}$ .

##### 4.2.2. Path planning and trials

The industrial robot is equipped with an integrated orbital sander which permit the management of the speed of rotation, contact force along a 100mm stroke. This tool makes it easy to take into account the positioning uncertainties between the various frames presented above. The trajectory is defined under Autodesk Powermill. Two types of trajectory are performed : area sanding (sanding windows) or a large trajectory along the master. (Figure 6) presents a patch on which sanding path is defined. (Figure 7) presents the first results for the sanding of a path. We observe the overlap area.

Another trajectory consists of sanding along the master. This trajectory is interesting in order not generate defaults between

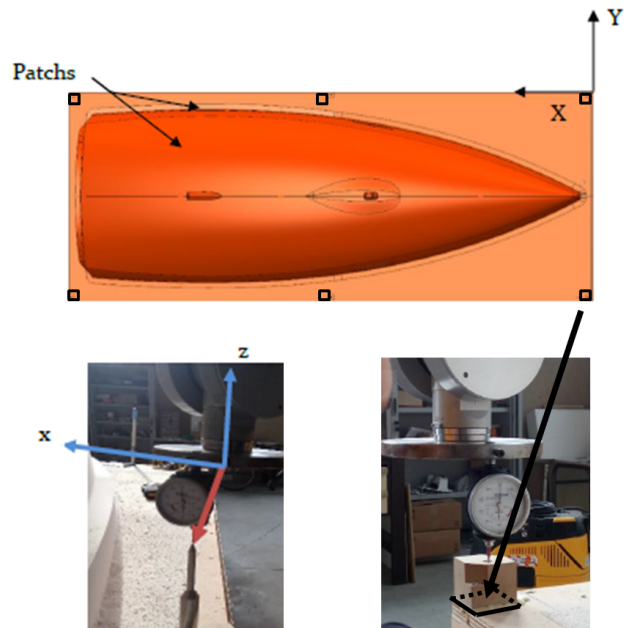


Fig. 5. Identification of the master and the TCP. At the top, a master top view where the elements of identification are located. At the bottom, left, identification of the TCP, At the bottom, right, identification of the master

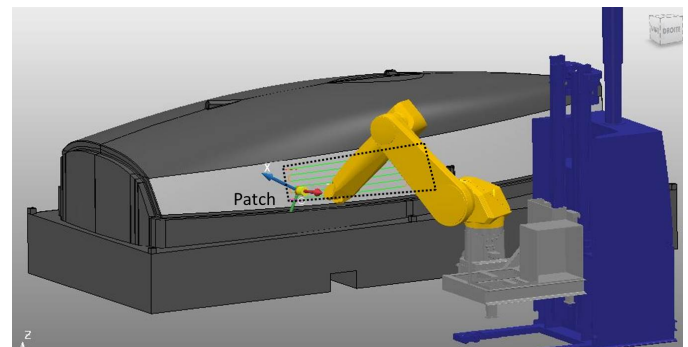


Fig. 6. Offline trajectory planification on a patch

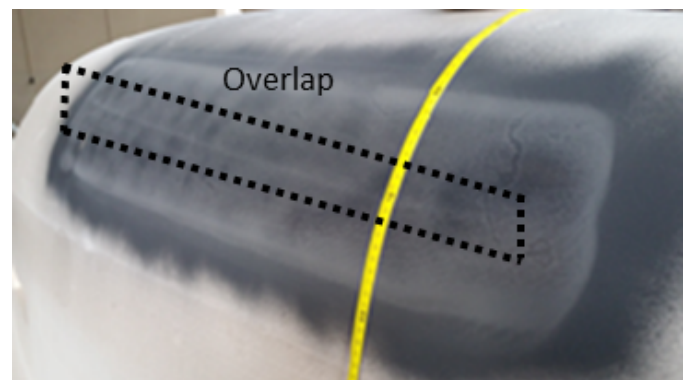


Fig. 7. Results obtained for the path sanding

sanding windows. Figure 8 presents different sequences of a video to present our implementation of the redundancy via geometric criteria.



Fig. 8. Process of redundancy management along the master

## 5. Improvement on the use of the kinematic redundancy for sanding application

In order to determine the way to improve the process behaviour, we give elements to be considered.

### 5.1. Sanding task analysis

Sanding task is sensitive to the parameters managing the process meaning the time spent on a given surface, the force applied on the given surface. Due to the shape of the master, the surface is not really easy to define : different variety of abrasive with different cutting power. In this way, taking into account the performance of the compliant tool, the expected behavior must improve :

- The positioning of the compliant tool regarding the master  $A_{TCPMaster}$
- The kinematic performance during direction change

$A_{TCPMaster}$  depends on the other transformation matrix and without tools to locate the TCP regarding the master, the transformation matrix depends on the other. Concerning the kinematic performance, criteria based on the kinematic capacity can be used [16]. This criteria takes into account the direction of

speed  $u$  and the Jacobian Matrix  $J$ . The criteria can be written as :

$$\Phi_v(q) = u_v^T (J_v J_v^T)^{-1} u_v \quad (2)$$

### 5.2. Mobile robot analysis

Mobile robot has been developed taking into account 2 technological brick : the AGV and the Industrial Robot. The AGV in the workshop is sensitive to the number of targets it can see with the laser scanner. Moreover, it exists an influence of the flatness of the floor which is taken into account by 2 inclinometers fixed on the AGV. The structure between the industrial robot and the AGV is compliant and its deflection is not negligible. The contact between the compliant tool and the master limit the vibration transmitted to the structure. The expected behavior must :

- limit the vibration/displacement of the structure meaning  $A_{AGVStructure}$
- improve our knowledge of the positioning of the AGV inside the workshop meaning  $A_{WorldAGV}$
- improve our knowledge of the positioning of the Master inside the workshop meaning  $A_{WorldMaster}$  : even if the master seems to be calibrated, it exists a gap between CAD-CAM and the real part.

$A_{AGVStructure}$  depends on the movement of the industrial robot on the structure. It would be interesting to evaluate the feared behavior for example a movement inside the plane of the structure (twisting of the AGV mast). It is necessary to limit the displacement of the 1<sup>st</sup> axis of the industrial robot. An optimization criteria could focus on the displacement on all the DoFs excepted  $q_1$  : it can be done considering that the reverse movement of the architecture should not consider  $q_1$  [17].

$A_{WorldAGV}$  depends on the positioning of the targets. An analysis should be performed.  $A_{WorldMaster}$  could be improved by a scan of the final part, in all the case, the compliant system can adapt itself to the shape.

### 5.3. Optimization

We are faced to a multi-criteria optimization. Kinematic performance and limitation of the deflection are often proposed as optimization criteria. It is moreover important to take into account the joint stops and wrist singularity. Literature proposes various solutions to perform it. One could be the projection of the criteria on the Kernel of the Jacobian Matrix [9,10].

## 6. Conclusion and Perspectives

In this paper, we study various topics linked to a mobile robot to perform sanding tasks. After a presentation of the control of a mobile manipulator based on two different robots, we

discuss the implementation of criteria and methods to manage the kinematic redundancy. We present two results in this paper : the first one is focused on the sanding of a patch and the second one consider the sanding along the master. The last example considers the implementation of a geometric criteria based on the projection of the sanding path on the axis of displacement of the AGV. Finally, we discuss the possibility to implement a more sophisticated use of criteria based to improve the mobile robot behavior. The perspectives are numerous with the development of an industrial solution to improve the behavior of the mobile robot. The characterization of the current behavior will allow us to define optimization criteria we will implement in the final version of the mobile robot. Robotic sanding quality will be compared to hand sanding. Only company's experts are able to characterize the work quality. Other research work will address the interaction between Human and this robotic system.

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