2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

On the robot based surface finishing of moving unknown parts by means of a new slip and force control concept

G. Milighetti, S. Bürger, H.-B. Kuntze

Abstract — **Fast and accurate robot based machining, finishing or cleaning of surfaces of geometrically complex manufacturing parts requires the introduction of flexible sensor based automation concepts. The industrial robots currently available on the market can not comply with such advanced requirements. In this paper a new concept for managing such challenging robot tasks is presented. It relies both on a flexible continuous slip and force control algorithm as well as on the use of a new slip sensor which is able to measure relative motion between the robot end-effector and the machined object surface. The smart slip and force control concept is applied to a robotic arm finishing the surface of an unfixed randomly moved object. Both theoretical approach and experimental results of ongoing research are presented in this paper.**

I. INTRODUCTION

The rising effort of automating more and more the different tasks in the industrial environment leads to an increasing complexity of the capabilities that a robot has to possess. Moreover, in the last years a new generation of interactive service robots has emerged in the public and private sector, opening up new scenarios in the robot market. In order to cope with these challenging demands robots have to be equipped with human-like perception organs which enable them to solve complex tasks interacting with the environment. Perception techniques are essential in order to sense both the internal state of the robot and its environment. Additionally it is an inevitable precondition for the interaction of robots with human operators. Challenging perception tasks require on the one hand sensors which cover the full range of human perception modalities, on the other hand the intelligence to combine and evaluate their complementary measurements.

The industrial robots currently available on the market are rarely provided with flexible sensor based control concepts. The use of cameras is mostly restricted to localization and inspection tasks as shown by the available products [1] and by market analysis (e.g. [2]). Also force-torque sensors due to their still low bandwidth and high noise rate [3] have not yet found wide spread deployment in surface finishing tasks and are often replaced by simpler and more reliable passive elements. Applications where other sensors are employed are unusual and in general standard interfaces are lacking. For these reasons the majority of surface finishing tasks such as polishing, deburring or grinding are still executed with a low automation level ([4], [5]) and either force sensors (e.g. grinding) or vision sensors (e.g. welding) are employed.

However, a robust and flexible automation of surface finishing applications requires at the same time the control of the normal contact force and of the relative tangential displacement (slip). Moreover, higher flexibility can be attained if the parts to be finished do not necessarily have to be fixed in the working space of the robot but can be moving.

Based on a novel slip sensor developed at IITB [6], a new control concept for robot based finishing of surfaces of unknown moving parts is presented in this paper in order to fill this gap. The central point of such a problem is that the robot has to receive information about the movement of the part during the finishing task. This can be hardly managed by means of a camera fixed in the environment because of probable covering effects of the robot arm. Therefore the proposed concept relies on the use of the slip sensor which is able to measure the relative motion between the robot end-effector and the surface of the part to finish.

Up till now the use of slip sensors has been mainly restricted to the fields of humanoid and mobile robots. In the case of humanoid robots, they have been used for grasping problems in order to assure the stability of the grasp (e.g. [7]) and also in some innovative solutions in legged robots in order to measure the slip of the foot on the ground [8]. In the case of mobile robots the sensor has been used in order to evaluate the movement of the robot in relation to the ground (e.g. [9], [10] and [11]).

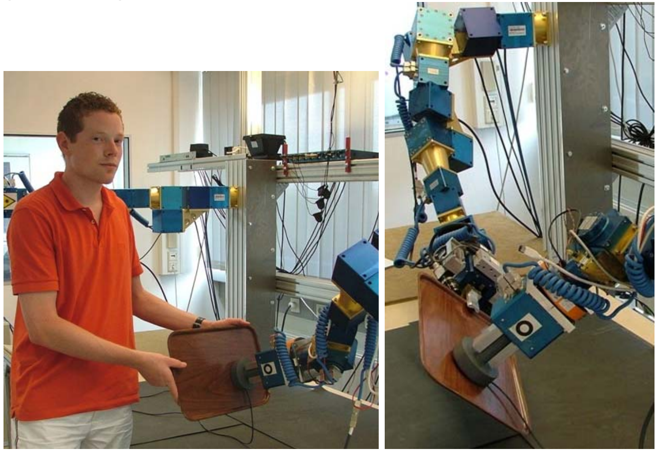

Fig. 1. Robot-based surface finishing a) interacting with the human b) autonomously

In addition, the proposed application is of importance in service and domestic robotics since the introduced slip sensor can be integrated in a robotic hand providing a basis for tasks such as wiping, cleaning or drying surfaces both for completely autonomous robots and also for robots in interaction with a human (Fig. 1).

II. SYSTEM ARCHITECTURE

A. *Robot Platform*

The experimental platform available at the Fraunhofer Institute IITB for the development and investigation of the skill described above consists of two 7DoF AMTEC robot arms and a 2DoF pan-tilt sensor head. For the communication and interaction with its environment the robot is equipped with different visual, acoustic and force sensors (Fig. 2).

The head is equipped with a stereo camera able to track predefined objects and with an acoustic sensor (microphone array) able to determine the position of sound sources. Moreover, an optical laser stripes sensor for accurately localizing objects at close range is integrated in one gripper.

Important for the skill presented in this paper are the two force-torque sensors mounted on the wrists and the slip sensor installed in one of the grippers in order to detect the relative motions between end-effector and surface.

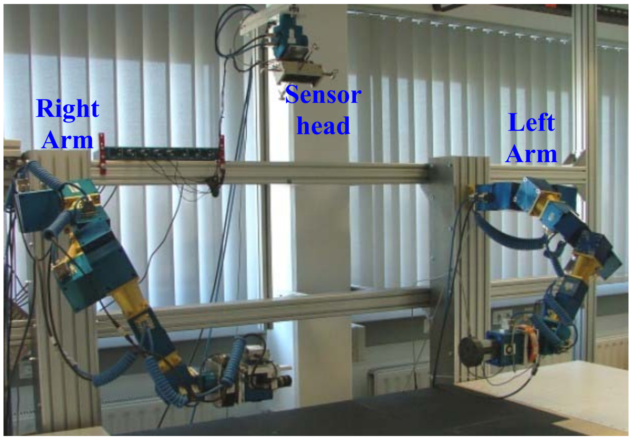

Fig. 2. Multi-sensor robotic platform

B. *Generic control architecture*

The basic structure of the control concept developed in order to supervise the robot throughout its task is shown in Fig. 3. The state of the robot interacting during its task with a human operator and the state of the environment is supervised with the help of internal (e.g. encoder) and external sensors (e.g. camera, microphone, force-torque).

At the upper hierarchy level, a discrete control processes the measurement values coming from the sensors and fuses them in order to generate diagnosis signals that contain quantitative information about the continuous state of the system (e.g. position of objects, sounds, forces). In a second step, this information is used for the identification of the discrete state or event providing the qualitative information about the present situation (e.g. a certain event has occurred). By interpreting the acquired knowledge about both the continuous and discrete state of the system, a decision unit supervises the actual task sequence, introducing a new appropriate action or adapting the present one if needed for overcoming unexpected situations and reaching the initial desired goal.

In order to perform a flexible task sequence generation and to have the possibility of a fast on-line task adaptation, a discrete task structure has been developed which assures a transparent and efficient instrument for the on-line decision and is also easily accessible by the decision unit. One way to obtain such a task structure is to base its architecture on a sequence of modules. Every task can thus be seen as the result of the execution of a chain of elementary actions called Primitive Skills (PS) each with its own sub-goal ([15]). Once the decision unit has determined the PS sequence that has to be performed and the most appropriate controller in order to execute the currently active PS, in the lower hierarchy level the continuous control assures that the currently active PS is managed by the optimal specific controller.

More details about the diagnosis concept and about PS can be found in [13] and [14].

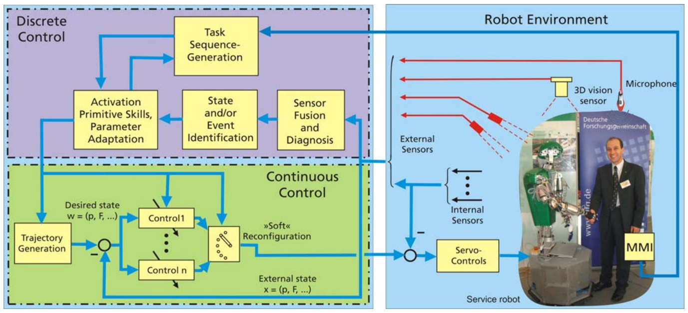

Fig. 3. Multi-sensor generic control architecture

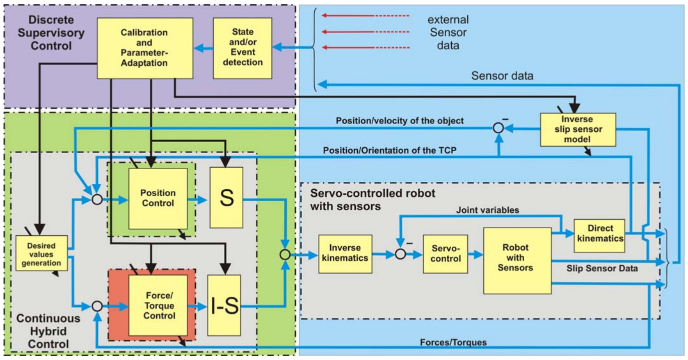

Fig. 4. Control concept dedicated to surface finishing

C. *Control concept*

On the basis of the presented generic architecture, a control concept has been designed in order to execute the proposed task of finishing or wiping parts with an unknown motion.

First of all the task is divided into four primitive skills:

- visual localization of the object;
- approaching motion;
- establishment of contact with the part surface;
- wiping motion.

This paper is focused on the PS responsible for the wiping motion which involves the most challenging control problem. For its execution an appropriate contact force with the surface and a compensation of the motion of the object have to be assured. The control scheme developed is shown in Fig. 4.

The contact force needed is assured by a classic hybrid force/position control. The motion of the object x_{obj} is estimated by means of a slip sensor. Such a sensor is integrated in the robot end-effector and is able to measure the relative motion x_{rel} between surface and robot.

$$\mathbf{x}_{rel} = \mathbf{x}_{TCP\_act} - \mathbf{x}_{obj} \tag{1}$$

Using the object motion, the initial desired trajectory can be adapted so that the relative motion of the robot tool on the surface is kept constant.

$$\mathbf{x}_{des\_new} = \mathbf{x}_{des\_ini} + \mathbf{x}_{obj} \tag{2}$$

It will be explained in the next section that an inverse model of the sensor is needed in order to interpret the measured counts and a calibration phase can be introduced in order to adapt this model to any unknown surface.

III. SLIP SENSOR

The key component of the proposed control concept is the slip sensor patented at IITB [6]. It uses the same working principle as an optical mouse. A light-emitting diode (LED) lights the surface, while a digital signal processor together with a CMOS sensor are responsible for the extraction of images and the detection of patterns. Comparing two images in sequence is thus possible in order to calculate how these patterns have changed between the two time instants and consequently the sensor displacement (Fig. 5). The covered distance is given in counts.

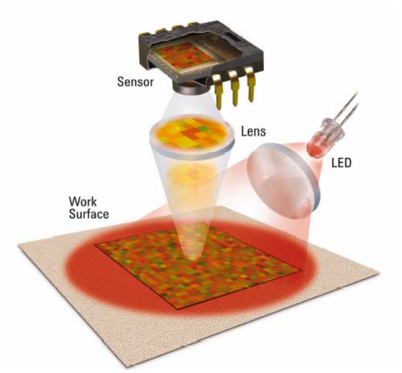

Fig. 5. Functioning principle of the optical slip sensor

The use of such a slip sensor offers the following advantages:

- it is very cheap;
- a miniaturization is easy (integrable almost in every tool);
- it works on every surface with some texture;
- the robot working on the surface doesn't hinder the measurements (contrary for example to a stereo camera);
- nearly no data processing is needed.

The only required data-processing is the transformation of the measured counts into a distance in meters. An accurate conversion factor has to be calculated so that the resolution of the sensor must be known as exactly as possible.

Due to its operating principle the resolution of the sensor is strongly dependent on the following factors [12]:

- distance of the lens foot from the surface;
- velocity of the sensor motion;
- material of the surface in contact with the sensor.

These uncertain and varying parameters have to be considered when building the inverse sensor model in the control concept. Since a force control is used for the alignment of the sensor to the surface (cfr. § II.C), the influence of the first factor can be assumed to be negligible in the presented robot-based task. On the other hand an investigation of the two remaining factors is required in order to determine the sensor characteristics and to make the sensor applicable to every surface before it can be integrated into the robot platform.

In order to have repeatable results, the sensor is mounted on a X-Y plotter robot (Fig. 6). Experiments with different velocities and on different surfaces have been performed.

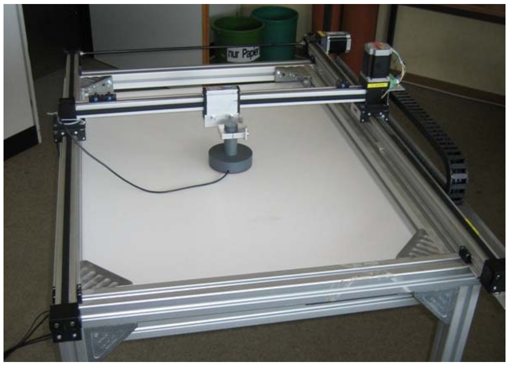

Fig. 6. X-Y plotter robot for the sensor investigation

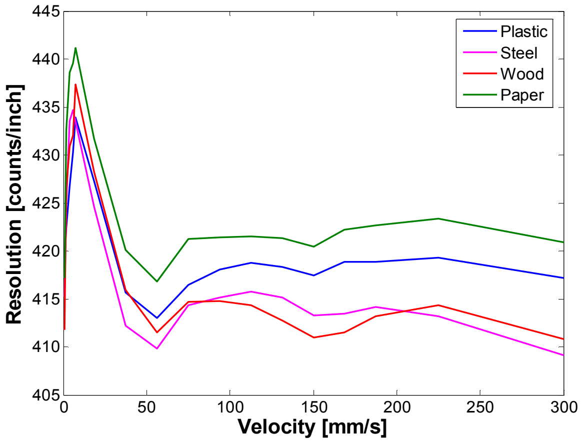

Fig. 7. Sensor resolution dependent on velocity and surface material

By measuring the distance covered by the plotter at different velocities and comparing it with the counts measured by the sensor, the lines shown in Fig. 7 were obtained for a sensor with a nominal resolution of 400 cpi (counts per inch) on four different materials (plastic, steel, wood and paper).

It can be observed that the dependences both on the velocity and on the material can not be neglected. The correct resolution can be always extrapolated knowing the surface and the finishing velocity. Once the resolution has been extracted an inverse model of the sensor can be evaluated which transforms the measured counts into distance covered.

$$d[mm] = \frac{counts}{cpi[counts/inch] \cdot 0,03937[inch/mm]} \quad (3)$$

In case of a-priori unknown surfaces, an adapted diagram for the resolution can be generated using an initial calibration phase. Once contact with the part is established, a rectangular trajectory with a different velocity for each side can be executed. In this way the first four points of the new a-priori unknown resolution line can be obtained and the whole line can be generated by scaling a previously existing one (Fig. 8). Experiments showed a reduction of the measurement error on a unknown surface from more than 2% (obtained with an existing resolution line) to almost 0% (with the calibrated one).

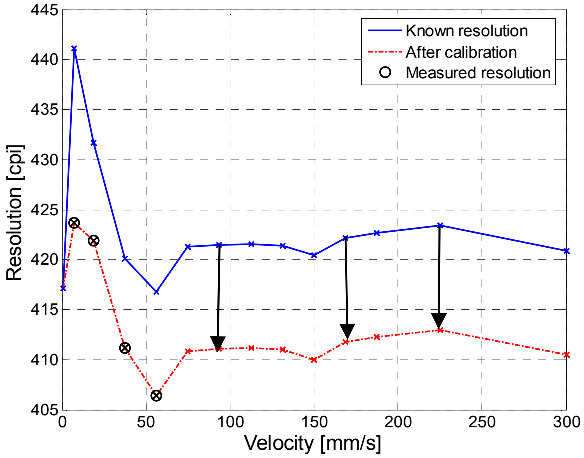

Fig. 8. Extraction of the resolution line for an unknown surface

IV. EXPERIMENTAL RESULTS

The hybrid slip and force control concept has been implemented and investigated experimentally. Three different classes of motion were considered:

- executing a desired trajectory on a still object;
- keeping a constant position on a moving object;
- executing a desired trajectory on a moving object.

In order to have comparable conditions the motion of the object was realized by fixing it to the X-Y plotter robot as shown in Fig. 9. Its exact movements can thus be measured and compared with the distances delivered by the sensor. This limits the task to maintaining a two dimensional motion, however this is without loss of generality since every motion in the 6DoF space can be reduced to a planar motion in the TCP frame.

The results presented were obtained for the case of wiping a cardboard box with a sheet of recycled paper applied on its surface (Fig. 9) for which the resolution was investigated previously as shown in Fig. 7. The two frames important for the presentation of the results are also shown in Fig. 9. The world frame (WF) is marked in yellow and the object frame (OF) in green.

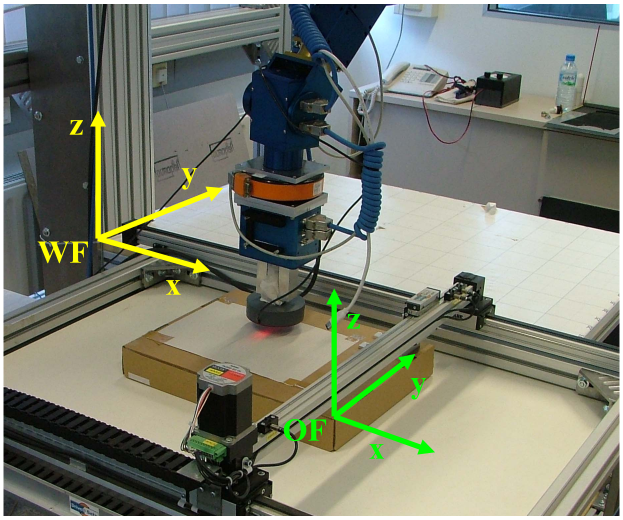

Fig. 9. Experimental set-up

A. Trajectory on a still object

The robot has to finish a surface of 100x100 mm^2 executing a meander with a maximum acceleration of 25 mm/s^2 and a velocity of 25mm/s. A desired contact force of 10 N has to be mantained.

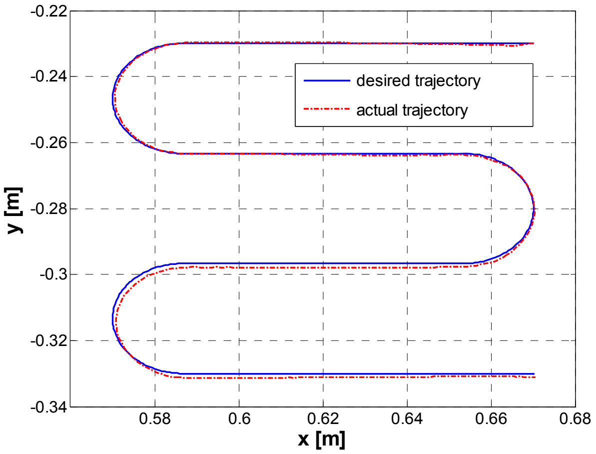

Fig. 10. Desired and actual trajectory of the robot wiping a still object (WF = OF)

The desired and the executed trajectories are shown in Fig. 10. Because the object has no motion the trajectory in the WF and in the OF are the same. It can be seen especially in the y direction that an error is accumulated during execution. This is due to an incorrect measurement or to an incorrect interpretation of the delivered counts.

So $\mathbf{x}_{rel} \neq \mathbf{x}_{TCP\_act}$ and consequently $\mathbf{x}_{obj} \neq 0$ leads to a permanent modification of the desired trajectory even if no real motion of the object occurred. However in Fig. 11 it can be seen that at the end of the motion the static error representing the residual measurement error is very small with a value for the x and y direction respectively of 0.5 and 1.2 mm (0.5% and 1.2% of the covered distance).

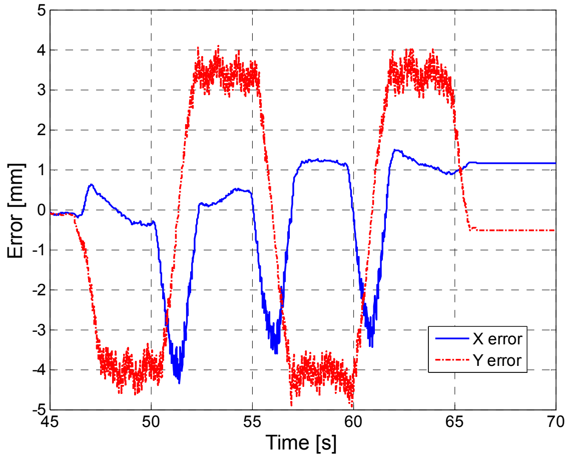

Fig. 11. Trajectory error of the robot wiping a still object (WF = OF)

B. *Constant position on a moving object*

In this second experiment class the robot has to keep its position on the surface while the object is moving. The diagrams shown are relative to a motion of the object of 50mm both in the negative x and y directions with a velocity of 37.5 mm/s and an acceleration of 30 mm/s^2.

Fig. 12 shows the robot position in the OF during the motion of the object. It can be seen that the overall error is divided into a dynamic error due to the robot control and a static residual error (1.1mm in x and 0.6mm in y) due to the measurement errors.

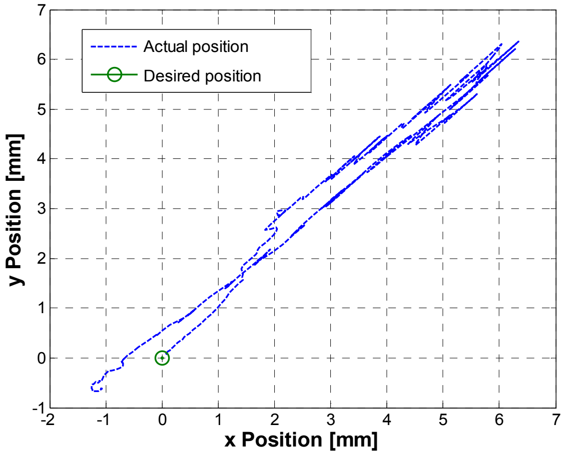

Fig. 12. Desired and actual position of the robot keeping its position on a moving object (OF)

The object displacement in both directions measured by means of the slip sensor is shown in Fig. 13. Although the obtained motions are not as smooth as in reality due to friction effects (just a slight tilting of the sensor strongly affects the measurements), to incorrect interpretations of the counts or to other failed measurements, a good accuracy was achieved.

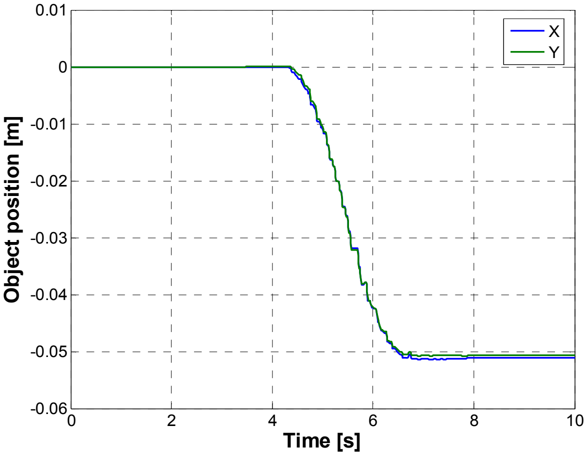

Fig. 13. Object motion measured by the slip sensor

C. *Trajectory on moving object*

As last case a trajectory on a moving object was considered. As in the previous experiments, the robot covers a 100x100mm^2 meander and the object moves 50mm along both x and y directions with the same velocities considered before.

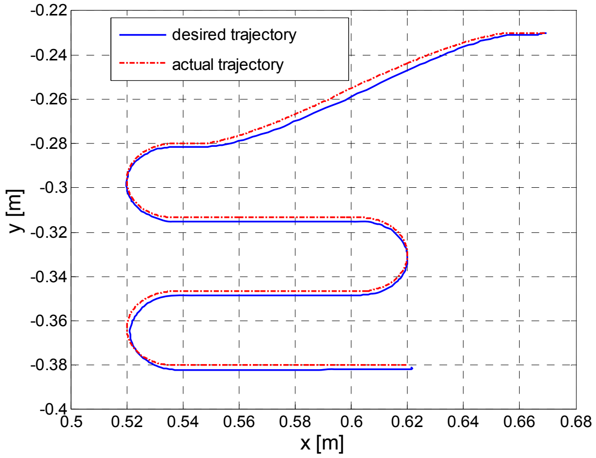

Fig. 14. Desired and actual trajectory of the robot on a moving object (WF)

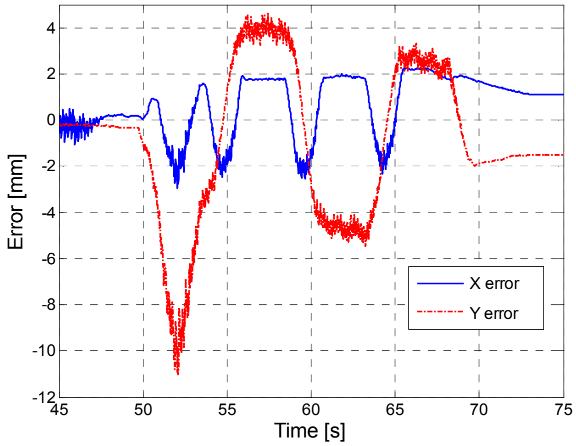

Fig. 15. Trajectory error of the robot wiping a moving object (WF)

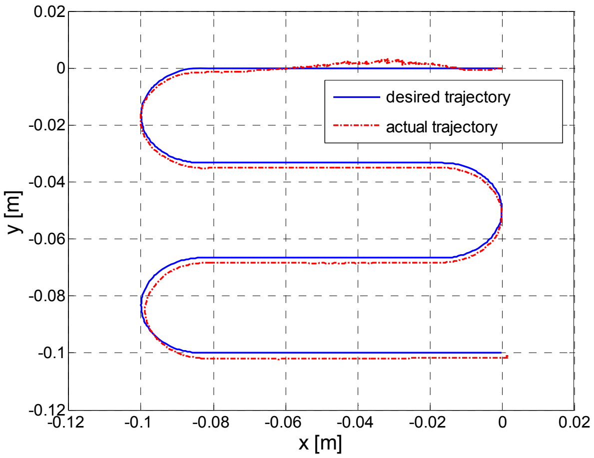

Fig. 16. Desired and actual trajectory of the robot on a moving object (OF)

In Fig. 14 and Fig. 15 the robot trajectory in WF and its errors are shown again. The control dynamics leads to a maximum error of 11mm in x and 3mm in y during the object motion while the measurement error can be clearly observed at the end of the task execution and it lies by 1.5% and 1.1% respectively for the two directions.

Finally, Fig. 16 shows the trajectory in the OF and again both the dynamic control error (particularly observable in the first section of the y-trajectory) and the small static measurement error can be recognized.

By means of the automatic calibration process described in §III.C the same results were also obtained on a-priori unknown surfaces reducing the measurement error for x and y respectively from 2% and 3% to 0% and 1%.

There are several applications where the presented sensor characteristics are sufficient, offering a cheap but at the same time robust solution. In case of higher requirements the performance of the sensor could be improved by using sensors with higher nominal resolution (1600 cpi) and by substituting the lighting function of the LED with a laser, thus extending the application field also to surfaces without a precise texture.

Considering the rather slow poor performance of the communication between sensor and robot (a new sensor value via UDP/IP ca. every 60 ms) and the slow dynamics of the test platform (control cycle ca. 30 ms), the achieved results are remarkable.

V. CONCLUSION

In this paper a novel slip and force control concept has been presented which can be applied to different industrial application. In order to cope with the industry requirement of introducing more automation in the finishing of surfaces,. The concept relies on an optical slip sensor able to measure the relative displacement between the robot end-effector and the surface, thus allowing the finishing of moving parts.

The sensor characteristics were investigated in order to have reliable measurements working even on a-priori unknown surfaces and finally the control concept was successfully implemented on the robot platform at Fraunhofer IITB. The first results presented are very promising and show how powerful the concept can also be for industrial applications.

ACKNOWLEDGMENT

The authors gratefully acknowledge that the research project presented in this paper has been supported by the Deutsche Forschungsgemeinschaft (DFG).

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