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Improved Control for the Impact Actuator

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***Abstract*— The impact actuator uses the momentum transfer during mechanical impacts to accelerate linear feed axes. As a result, nearly abrupt changes in velocity can be achieved. So far, the impact and thus the velocity change have been idealized as abrupt within the controller. Since very high but not infinite accelerations occur, no actual jumps in velocity can be achieved, resulting in position and contour errors at corners in planned trajectories. In this paper, an extended control method is considered which takes into account these physical limitations of the approach in order to improve the system behavior. Using a reference trajectory, a comparison is made between regular trajectory planning, the previous control method with idealized impacts, and the new approach with improved control.**

I. INTRODUCTION

Feed drives are used to generate the required movement between the workpiece and the tool in machine tools and other production equipment. Important requirements here are high dynamics, contour accuracy and, for many processes, a constant path velocity. Due to the requirements on the feed axes, mainly electromechanical drives such as ball screw drives, rack-and-pinion drives, but also direct drives without mechanical transmission elements are used, with different advantages and disadvantages in each case. An overview of these is given in [1].

To follow given contours quickly, the feed axes dynamic is an important point in the drive selection [2]. The dynamic is limited by the available drive force, as well as the compliance of the machine structure. To reduce the excitation of the machine, it is necessary to limit the acceleration and especially the jerk of the drives [3]. If the process requires a sharp turn, all axes must first be fully decelerated before accelerating in the new direction. Ramps with jerk and acceleration limits can be used for this defined stop [4].

If a constant path velocity is advantageous from a process engineering point of view, for example in beam processing [5], the corner can be rounded off by additional path segments. The easiest option is to use a circle segment instead of the corner. This can be further improved by using additional path segments to smooth the transition to the curvature like in [6] or [7].

In order to positively influence the general properties and especially the dynamic of a machine, there are many different approaches, which can be generally divided into control engineering, mechanical and mechatronic approaches. Mechanical improvements can be achieved, for example, through structural optimization of the frame, which enables higher accelerations and returns [8]. Alternatively, machine components can be improved through topology optimization to reduce moving masses [9]. Another approach is to mechanically decouple the drives from the frame, for which strong spring-damper elements are used [10].

Control engineering approaches optimize the system behavior without changing the mechanical structure or using additional actuators. Exemplary approaches here are the extension of the classical cascade control by specific consideration of the position difference between table and motor [11], or inserting additional loops to increase the bandwidth [12]. Model-based controllers can also achieve an increase in dynamics, provided good knowledge of the system [13].

Mechatronic approaches are based on the use of new active or semi-active elements in the system. An example is the above-mentioned decoupling, but with a spring-damper that can be actively controlled [14]. The element does not have to be an active motor here, it can also be a mechanical spring-damper whose properties can be actively changed during operation. This option allows for even higher dynamic enhancement, but is also associated with higher costs than the passive method. A different approach is a semi-active actuator that introduces additional damping into the system through friction in order to specifically suppress vibrations [15]. Another possibility is the use of redundant axes to realize large-scale motion by large, heavy axes and small-scale dynamic motion by a light, parallel axis. The control of these axes is described for example in [16].

Another approach that increases the dynamics of feed axes is the impact actuator, which uses mechanical impacts from an additional actuator for momentum transfer to abruptly accelerate the base axes [17–19]. As a result, almost abrupt changes in velocity are achieved at the machine table, allowing corner driving without stopping in a multi-axis operation. Since the acceleration occurs exclusively via the impact, the base drive only has to compensate for disturbing forces and the excitation of the frame is significantly reduced [17].

As the impacts are actually continuous and the achievable acceleration is therefore limited, no actual velocity steps can be achieved on the base drive. This results in an overshoot when executing planned corners. For this reason, the concept will be examined in more detail below, the deficits will be identified and improvements to the control system will be made on this basis.

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II. THE CONCEPT OF THE IMPACT ACTUATOR

The approach of the impact actuator uses the transfer of momentum during an impact to accelerate feed axes to the maximum. For this purpose, an auxiliary actuator with additional mass is attached to a base drive. In both directions, the additional mass and the base drive have contact surfaces against which the mass hits during operation. If a velocity change is to be made at the base drive during operation, the actuator strikes against the frame at the velocity required for this. The velocity of the actuator $v_{\text{imp},0}$ is calculated using the inelastic collision, shown in (1). For this, the masses of the actuator m_{imp} and the base m_{b}, the velocities of the base before $v_{\text{b},0}$ and after $v_{\text{b},1}$ the velocity change as well as the coefficient of restitution k_{imp} are required.

$$v_{imp} = \frac{v_{\text{b},1}(m_{\text{b}} + m_{\text{imp}}) - v_{\text{b},0}(m_{\text{b}} + k_{\text{imp}} \cdot m_{\text{imp}})}{m_{\text{imp}}(1 + k_{\text{imp}})} \quad (1)$$

The calculation of the actuator velocity after the impact is calculated accordingly. The masses should be known from construction, while the impact number is determined experimentally depending on the velocity. This identification is described in [19].

Between two impacts, in theory the actuator can move freely. A low-jerk path is recommended, which catches the actuator after an impact and continuously transfers it to the next impact. A more detailed discussion can be found in [17].

A. Test bed

To investigate the concept, a test bed was set up, which is shown in Fig. 1. It consists of a cross table with linear direct drives (LDD) as base drives, which are moving the machine table. In addition, both axes are equipped with an impact actuator (Imp). The actuators are mounted on the base of the dedicated axis and can move independently from the base drive. The actuator of the x-axis is a voice coil, while the actuator of the y-axis is a linear direct drive in tubular design. An additional mass is attached to each, which is guided parallel to the feed direction. Contact geometries intended for the impact are attached to both masses and to the bases in both directions. For a good impact with a clear direction and without lateral forces, the geometry combination sphere on plane was selected. The contact bodies are made of hardened steel in order to transfer the high impact forces as abruptly as possible. The two axes and both actuators each have a position measuring system, additional acceleration sensors can be attached to the structure. The test bed is mounted on a frame made of aluminum profiles, which also houses the control cabinet. All four motors are driven by industrial servo drives and use a cascade control of position, speed and current loop. In addition, force feedforward controls are implemented for the quasi-redundant axes. Setpoint generation and the position- and velocity-loop of the cascade control are implemented in Matlab Simulink and run on a Speedgoat rapid prototyping system. A more detailed description of the construction and dimensioning of the test bed is given in [18].

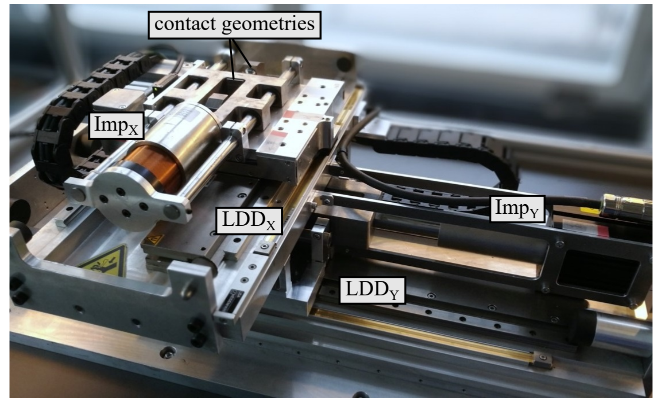

Fig. 1. Test bed (refer [19])

B. Simulation model

In order to be able to test new control approaches without risk, a simulation model of the test bed was also developed. The multi-body model used for this purpose is shown in Fig. 2. The individual masses are modeled as rigid single bodies. The motors are not modeled separately, the acting forces are shown in the figure and affect the masses directly. In addition, the contact geometries are indicated on the x-axis, those of the y-axis are not visible, since this axis is perpendicular to the image. A friction model is also implemented for each axis. The dimensions and masses of the individual bodies are taken from construction data, while the other parameters are identified on and matched to the test bed. The modeling of the continuous impact is based on the material properties and is done according to [20]. A more detailed description of the single-axis multibody model is given in [18].

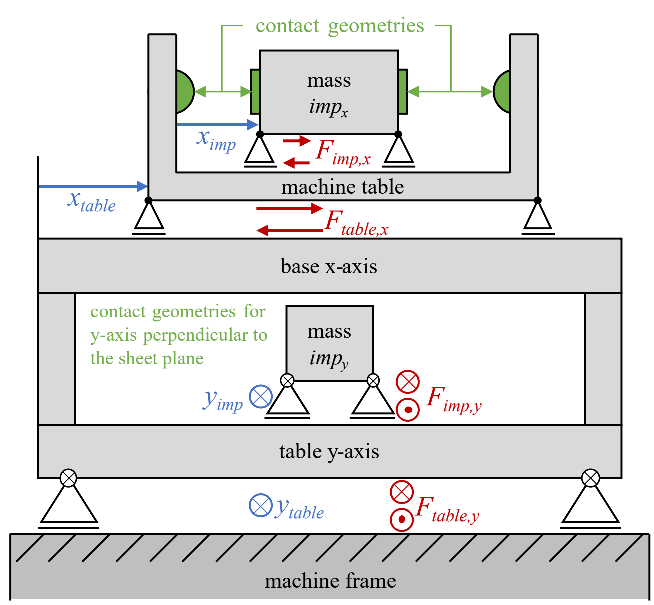

Fig. 2. Multibody model of the 2-axis test bed with impact actuators

C. Achievable dynamic and limits of the concept

With the help of the additional actuator, accelerations of up to $500\,\mathrm{m/s^2}$ can be achieved at the basic drive depending on the velocity changes, shown in [17] for the x-axis. When driving an edged profile with constant velocity in [19], accelerations of more than $200\,\mathrm{m/s^2}$ are achieved. The actuator control is designed so that the mass hits the impact surface at the exact moment, the base axis is supposed to stop. The position and velocity course of the x-axis, which is to stop in a corner at $50\,\mathrm{mm}$, is shown in Fig. 3. At time $t_0 = 1.25\,\mathrm{s}$ the actuator hits the impact surface in negative direction with the velocity calculated according to (1).

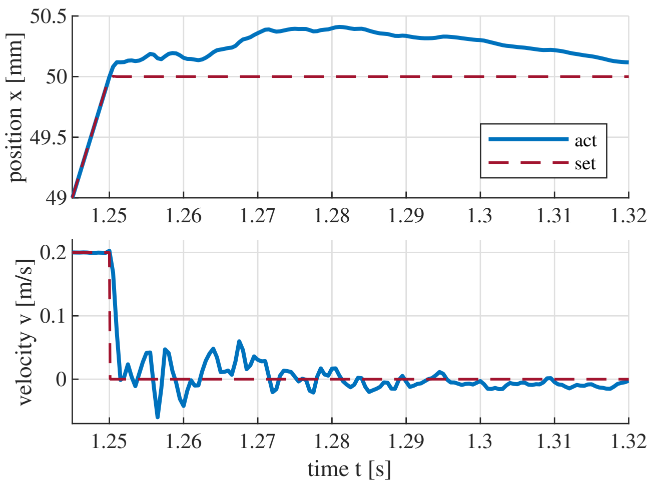

Fig. 3. Limit of velocity change with impact actuator (refer [19])

It can be seen that a position error of the axis occurs after the impact. In addition, the actual velocity cannot follow the set value and oscillates in the following. This is primarily attributed to the following factors:

- The velocity of the axis changes very quickly, but not abruptly. Since the axis therefore needs a short time to decelerate, the axis oscillates beyond the set position. Especially the initial overshoot at $t = 1.25\,\mathrm{s}$, which persists until around $t = 1.26\,\mathrm{s}$ is caused by this.
- Due to dead time in the system, which in this dynamic case has a similar order of magnitude as the actual deceleration process, the velocity controller receives the change delayed. With the step in the setpoint and the delayed actual value, the controller is stimulated to oscillate.
- Due to the integral component in the velocity controller, it is inert in the event of abrupt changes. Although the axis is already beyond the set position, the velocity controller continues to push the axis. This issue in combination with the dead time probably causes the subsequent overshoot after the initial plateau of the error.

In summary, the dynamics are very high, but systematic and control-based errors are present. Since these most important factors are known and reproducible, an improved control is presented below.

III. IMPROVED CONTROL DESIGN

The improved control is primarily based on the improvement of the feedforward control. Based on the issues described above, the following changes are implemented:
The impact duration is taken into account in the path planning for axis and actuator. From the consideration of several impacts of different velocities, it can be seen that the dependence of the impact duration on the velocity is very small and is therefore neglected, resulting in a constant duration. The shape of the force and thus of the acceleration during the impact over time (ref. [20]) is approximated by a parabola. The change of velocity and position can thus be calculated over the impact duration. The time of the first contact is subsequently pulled forward in such a way that the change is over exactly when the base reaches its target position and velocity. The path planning of the actuator is therefore adjusted so that the actuator strikes the impact surface at the initial point in time and is kept constant for the duration of the impact.
To prevent the velocity controller from pushing beyond the set position after an impact, the integral component is reset after an impact. A similar approach for ball screw drives is described in [21] to reduce the negative quadrant glitch after a direction change. The reset is executed at the moment when the impact as described above is completed.
The calculation of the actuator velocity for impact is still done according to (1) with experimentally identified coefficients of restitution. The implementations described in point one are taken into account thereafter. This results in the target profile being slightly rounded in the corners. A solution for the dead time problem is not implemented initially. It is expected that a trajectory better adapted to the achievable dynamic will reduce the error due to dead time. In addition, resetting the integral component also fixes part of the error caused by dead time.

IV. VALIDATION

A comparison of the new control approach, referred to as *Imp** in the following, with the previously used control, referred to as *Imp* in the following, will be made. To display the magnitude of improvement, the comparison is made against a profile where the axes stop in the corners with limited acceleration and jerk, labeled as *Stop*.
The validation is initially carried out using the simulation model due to the simpler implementation and accessibility to more signals and data. The new control strategy is then also tested on the test bed. The test contour, where corners occur at all possible angles, is shown in Fig. 4. There are corners parallel to the base axes, where the axes are accelerated from zero to the target velocity or decelerated the other way around to zero. In the case of inclined angles, a partial change of velocity occurs in one or both axes, sometimes with a change of sign. The contour is traversed at a constant velocity of $0.2\,\mathrm{m/s}$ starting from the origin in a counterclockwise direction.

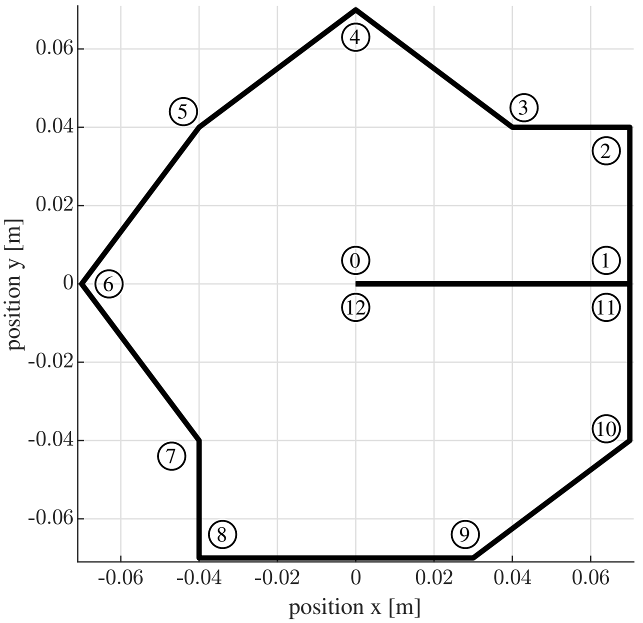

Fig. 4. Reference contour

This means that from the starting position 0, corners 1 to 11 are executed one after the other until the axes are stopped again at position 12.

A. *Contour errors at corners*

In Fig. 5 corner 2 is considered as an example. It is evident that the corner is overshot less with the new control. The simulated and measured data for the complete contour and all other corners is available on DaRUS [22].

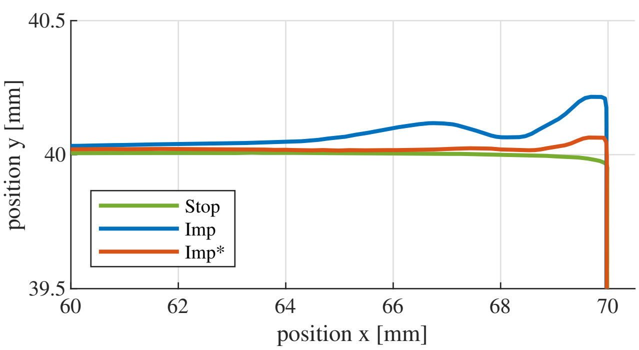

Fig. 5. Zoomed in trajectory for the different control methods

In the following, Fig. 6 shows the position (top) and the velocity (bottom) of the y-axis for this corner in detail.
First of all, the time advantage of using the impact actuator is evident. In both controls, the axis is already at standstill well before the axis reaches the target position with continuous deceleration (*Stop*). It is also evident that the axis with *Imp** overshoots less than the axis with *Imp*. The correction of the occurring error is also faster afterwards.
Comparing the velocity of the two impact controller, it is noticeable that the curves are identical during the actual

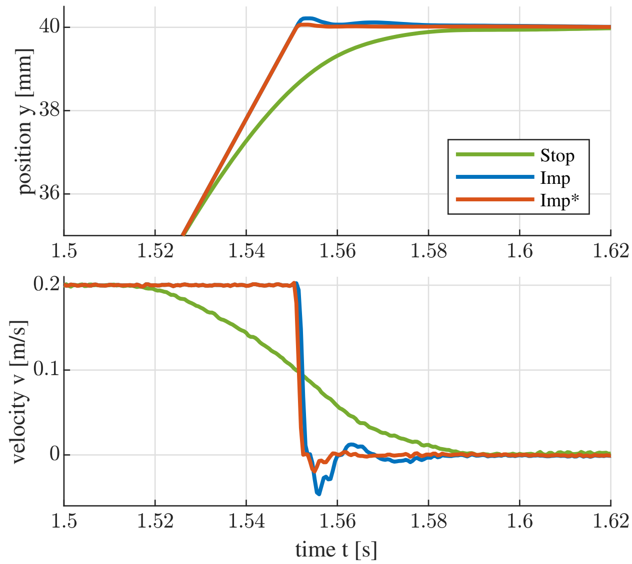

Fig. 6. Position and velocity of y-axis with different control methods

impact. Only after this a larger error occurs for the *Imp* curve. It is barely noticeable that the *Imp** curve is slightly pulled forward. As a result, the overshoot across the corner is smaller, which consequently leads to a lower leveling out by the velocity controller. There is still a minimal overshoot when using the new control approach. On the one hand, the problem of dead time still remains in the system. On the other hand, not every impact can be perfectly pre-controlled for every boundary condition and deviations in the actual velocity of the actuator also lead to an error in the velocity curve of the axis.

B. *Characteristics of the actuator during impact*

Fig. 7 shows the curve of the position of the y-actuator for the considered corner.
It can be seen that the curves of the actual values are almost identical for both controls. The impact with *Imp** is only slightly pulled forward. The difference in the curves of the set values is more relevant.
The set curve of *Imp** places the zero position, which corresponds to the contact area in negative direction, earlier and holds it for a short period of time. As a result, the difference between the set and actual curves before and after the impact is almost identical. Apart from a slight offset, the recoil behavior corresponds to the expected curve.
Meanwhile, the set value of *Imp* is zero only for exactly one timestep. As a result, the difference between set and actual values is several times larger after the impact. In addition to the problem of the impact occuring too late for the base axis in this case, this also leads to an increased leveling out by the actuator. The resulting compensating force acts as a disturbing force on the underlying base axis.

C. *Effect of the velocity control reset*

Fig. 8 shows the effect of resetting the velocity controller. The initial error of the contours with and without reset after

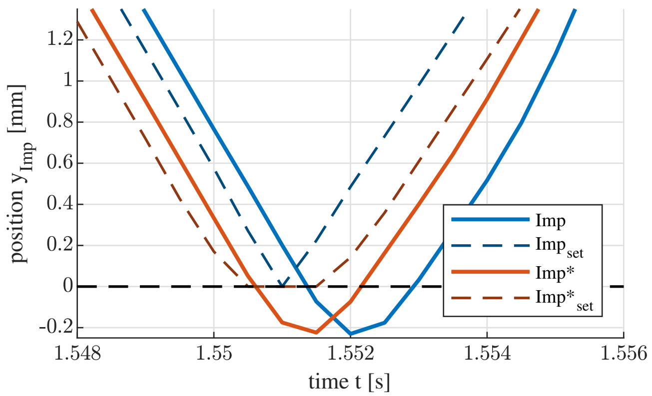

Fig. 7. Position of the actuator for previous and new control strategy

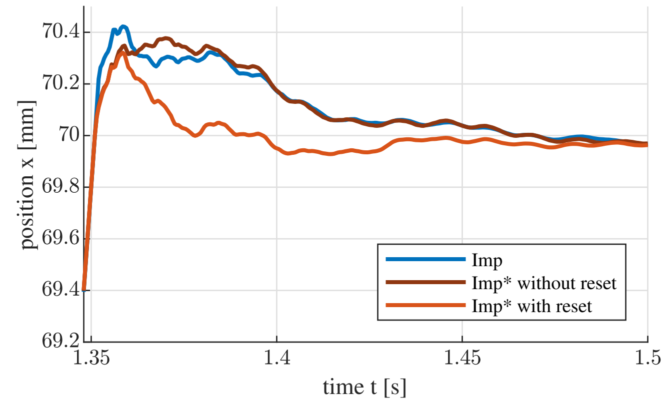

Fig. 9. Improvement of the new control on testbed

the impact is identical. Afterwards, as in the previous process *Imp*, a new upswing of the error occurs. This upswing is slightly smaller in the case with reset of the velocity controller than without. The remaining error, which stays almost constant for a short time in both cases, can also originate from the movement of the actuator, whose reaction forces during acceleration and deceleration act as disturbing forces on the main axis, despite the implemented feedforward control.

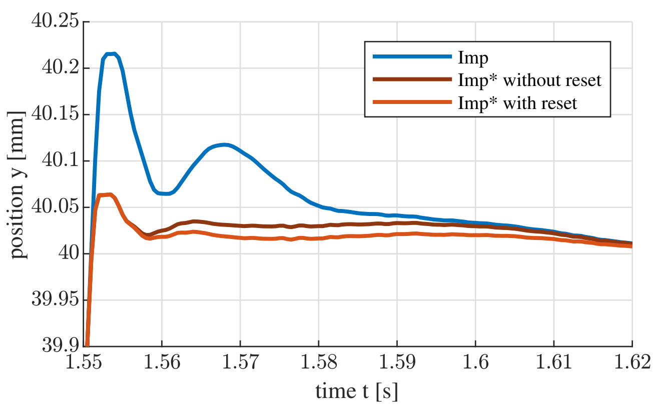

Fig. 8. Improvement of the new control with reset of the velocity loop

Depending on the corners, angle or velocity, the influence of resetting the velocity controller varies, but the behavior is not worse than without resetting in any of the investigated corners.
Fig. 9 shows the performance of the different strategies on the testbed exemplarily for the x-axis in a corner similar to ①. It is evident that the initial error is reduced with the new strategy (*Imp*), but the improvement is lower than in the simulation. This can be explained by inaccurate identification of the impact parameters or tracking errors occurring in the motion of the actuator, which leads to an incorrect impact. The influence of inaccuracies and control errors shall be examined in more detail in future work. After the initial peak, the error is slowly reduced with the former strategy as well as without reset, while the reset (*Imp**) leads to a significant improvement.

D. Quantitative comparison

For a concluding evaluation, the peak contour error, axis error and path error for *Imp* and *Imp** are compared in table I. For *Imp** the case without velocity controller reset is additionally considered.
For evaluation, the corners discussed above (② for simulative and ① for experimental) are considered. The integrated mean axis error e_{ax} calculates the mean value of the absolute differences between set value pos_{set} and actual value pos_{act} according to (2) and is calculated for both, the x and the y-axis.

$$e_{\text{ax}} = \sum_{k=1}^{n} \frac{|pos_{\text{set}} - pos_{\text{act}}|}{n} \tag{2}$$

The accumulated path error E_{path} calculated according to (3) serves as second reference value and quantifies the area of the faulty contour:

$$E_{\text{path}} = \int_{k=0}^{n} dist(k)dl \tag{3}$$

with $dist(k)$ describing the shortest distance between the actual position at measuring point k to the ideal contour which is integrated over the length of the contour. This means that it is not the time-dependent axis error that is described, but the actual deviation from the ideal contour. The maximum value of $dist(k)$ is also the maximum contour error $e_{c,max}$.

TABLE I

COMPARISON OF ERROR VALUES

Error value	Imp	Imp* w/o	Imp*
$e_{\text{c,max,sim}}[\mu m]$	216	71.5	73.8
$e_{\text{ax,x,sim}}[\mu m]$	101.9	59.8	51.8
$e_{\text{ax,y,sim}}[\mu m]$	57.7	27.3	18.9
$E_{\text{path,sim}}[mm^2]$	0.837	0.404	0.279
$e_{\text{c,max,exp}}[\mu m]$	423	377	321
$e_{\text{ax,x,exp}}[\mu m]$	124.2	127.5	56.4
$e_{\text{ax,y,exp}}[\mu m]$	305	223	276
$E_{\text{path,exp}}[mm^2]$	0.524	0.523	0.377

It can be seen that taking the impact time into account reduces the initial error peak, while the controller reset reduces the mean error and the area of the faulty contour. In the experimental results, it is noticeable that the values for the y-axis are significantly higher than those for the x-axis and also receive a smaller improvement with the new strategy.

V. CONCLUSION

The dynamic of feed axes is significantly increased with the impact actuators. Good contour fidelity at full velocity is already possible with the existing control. Although the contour was violated, the error is significantly smaller than the deviation that has to be accepted, for example, with grinding over the edge in order to maintain a constant path velocity.

In this paper, the reasons for existing errors are considered and improvements are proposed based on them. In particular, the systematic error due to the idealized description of the impact and the resulting neglected impact duration in the control is addressed. The new approach uses a simplified description of the impact via a parabolic force curve with constant impact duration. The result is a distinct increase in contour fidelity, since the time period of the velocity change is known and the timing of the impact can thus be adjusted even better. This primarily improves the maximum error in a corner. The additionally introduced reset of the velocity controller also improves the behaviour, especially the reduction of the error after the initial peak.

As can be seen in the experimental results, the improvement achieved by the actuator in the y-axis is significantly lower than in the x-axis, which is mainly due to inaccurate identification and non-optimal controller design of the actuator. A new drive and subsequent re-identification should improve the behavior and bring the improvement closer to the x-axis. Nevertheless, deviations occur even with the new strategy, which can also be seen to a lesser extent in the simulation. The most important boundary condition for the entire concept is to execute the impact at the exact time and at the required velocity. Small deviations due to tracking errors or dead time lead to a non-ideal impact and thus to a contour violation. These need to be reduced further, for example, the expected error during the impact can be identified and compensated for by means of extended identification process. Alternatively, the use of learning control approaches could be conceivable.

In the future, taking the impact duration into account will also make it possible to modify the previously pursued approach of increasing the dynamics of the axes as much as possible. If softer materials are used for the contact geometries instead of hardened steel, the impact lasts longer and the maximum force decreases and thus also the maximum acceleration. Provided that the impact is still reproducible, this change can be used to make the impact actuator more attractive for applications that require high accelerations, but not to the extent that have been encountered so far.

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