Application note
"Generating precise and smooth multi-axis reference motion trajectory with IMP library"

Keywords:
Automatic transition (AT), ETEL device interface (EDI), geometry fitting (GF), interpolated motion planning (IMP), motion trajectory, tracking error

Disclaimer
This note is based on the stated hardware and software as well as the corresponding documentation. This note is therefore only valid for the described installation. New hardware and software versions may need to be handled differently. Additional modifications may occur without notification. Please refer to the detailed description in the specific manuals.

Abstract

This application note explains how to use the ETEL's Interpolated Motion Planning (IMP) library to create a complex, high-precision, yet smooth synchronized multi-axis reference motion trajectory for various applications such as many laser based processes, dispensing systems, automated inspection, etc. The note also describes in detail how to make use of its powerful Geometry Fitting and Automatic Transition features.

Introduction

Trajectory generation application nowadays is demanding high-precision geometry motion. This note explains how to implement synchronized multi-axis interpolated motion planning that requires high-precision geometry fitting and smooth transition between motion segments thanks to the ETEL's IMP library.

The main goals for the IMP library are to:

- Construct a collection of lines, curves, and other geometric objects into a theoretical reference trajectory for real-world motion.
- Interconnect separated geometric objects with smooth automatic transition.
- Comply with the required reference kinematic limits.

How trajectory precision and smoothness impact the final product

Ever since the market started to push for precision and high-end specification, reference trajectory precision has been the key to keep the best product quality in the repeated process. As the specifications are getting more and more complex and difficult to achieve, the impact of precision is a decisive factor for the quality of the final product. The real-world motion system performance is however limited by the quality of generated reference trajectory. Without a precise theoretical path for real system to follow, it is then difficult to expect that the final product quality is going to be good.

On the other hand, the trajectory should be a feasible motion plan for a real-world motion system. If the reference trajectory is too violent or discontinuous, the real-world system fails in following the given trajectory. In the worst case, the system might fail to complete the trajectory due to self-inflicted disturbance.

In addition, it gets more difficult to know whether the trajectory is feasible or not when the target trajectory is more complex, multi-segmented with non-constant kinematic conditions. Assuming that you must hand-tailor the finely optimized trajectory every time a new modification is needed, this can cost a substantial amount of working hours.

To help with the aforementioned technical challenges, the IMP solution provides:

- Easy and intuitive way to plan interpolated motion with multiple axes.
- High-precision trajectory generation.
- Various and flexible geometry fitting shape primitives.
- Automatic smooth transition between defined positions.
- Respecting different kinematic constraints (velocity, acceleration, jerk…)
- Trajectory execution management.
- Event management during the trajectory.

Planning multi-axis motion trajectory for IMP implementation

With IMP, you can plan the whole trajectory based on the project requirements. The trajectory in IMP application is a collection of motion segments, position triggers, and timestamp markers. Once all the motion segments are added to the trajectory, the trajectory has to be compiled. This operation will guarantee the kinematic bounds that you have initially set.

When the trajectory motion is required during the process, the trajectory can be categorized into two different notions, as displayed in Fig.1.

- **Shape**: a complex shape could be realized with geometric fitting, such as lines and arcs. More complex shapes can be based on parametric curves with Bezier or polynomial equations.
- **Transition**: any discontinuous process within the motion plan is considered as a transition. During the transition, no work is done until it reaches the target transition point. For example, a trajectory with multiple number of shapes needs a transition path between the shapes. Each transition has to find the most optimal path within the workspace.

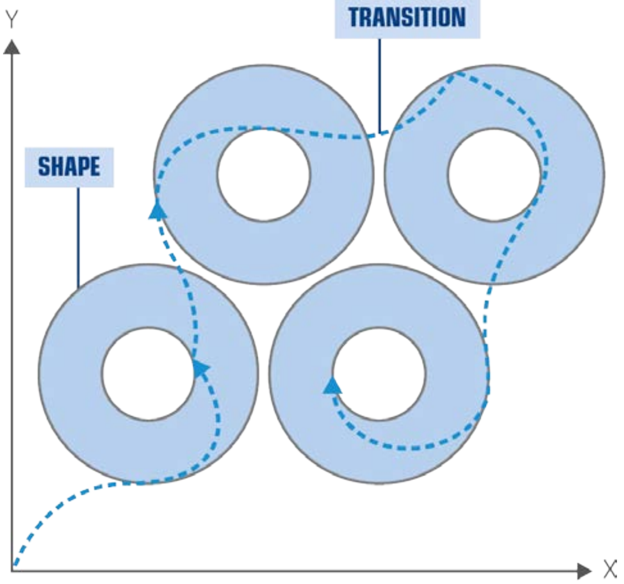


Fig.1 Converting idea into IMP trajectory segments.

Both shape and transition can be translated into motion segments, which are the essential parts of the IMP trajectory. To create motion segments, you can rely on two types of elements: Geometry Fitting (GF) or Automatic Transition (AT), see Fig.2.

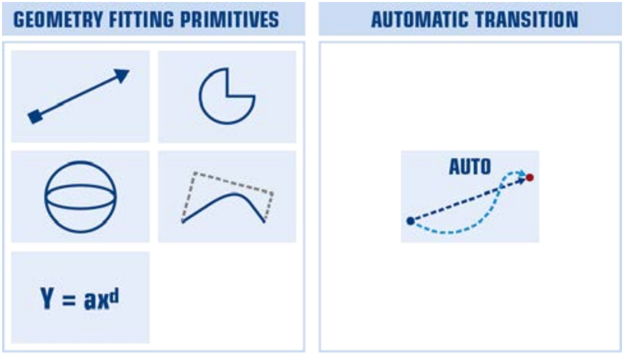


Fig.2 Shapes (Geometric fitting lines, arcs, parametric curves…) and transition segments.

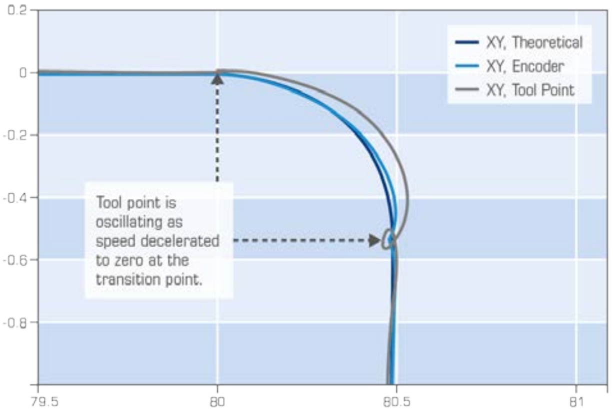
A simple line shape can also be used as a transition motion, and it is the shortest geometric fitting path. However, it can lead to important tracking error, or lower speed at transition points. On the contrary, IMP Automatic Transition segment allows entering/exiting of shape motion segment at maximum speed, and deciding the optimal transition shape automatically. That is to say, a shape-to-shape transition can simply be done with the Automatic Transition.

In addition, 2D position triggers and timestamp markers are optional element of the IMP trajectory. You can add them into the trajectory whenever required. For example, equipment such as camera, printing nozzle or laser gun action can be synchronized with the event of the position trigger.

Geometric fitting only vs. smooth path included trajectory

Transition of motion segment can be made either with geometric fitting or with smooth path. Sometimes, a transition point is where the worst shock to the real system due to acceleration coming from the kinematic vector direction and the magnitude change can be observed. This is visualized in Fig.3.

In addition, if the transition is at zero speed, the tool point has a risk to oscillate due to deceleration at transition point.



Tool point is oscillating as speed decelerated to zero at the transition point.

Fig.3 XY position plot of transition trajectory at zero speed and of tool point oscillation.

In case of motion planning with IMP, the correctness of calculated path compared to ideal is guaranteed at theoretical trajectory level. Each corner in geometric motion is rounded to fit into the specified trajectory tolerance, so that the theoretical motion path can smoothly be realized with a non-zero speed, as can be seen from Fig.4.

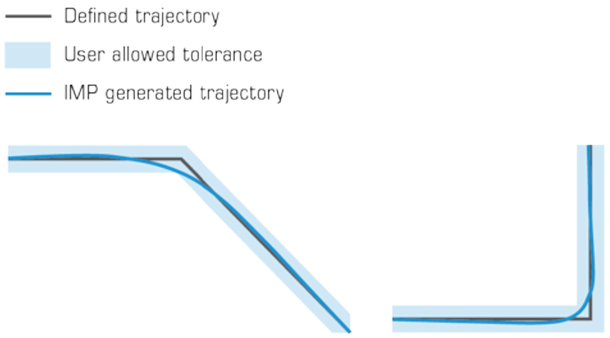


Fig.4 Geometric fitting error tolerance can be freely configured.

No matter what kind of combination you have specified, the IMP trajectory ensures that the calculated error of motion path remains under the trajectory bound limits. As a matter of fact, it is possible to plan a whole IMP trajectory with GF segments only when necessary. However, the best performance is usually observed when AT segment is used for transition during the motion process. For example, AT segments is used to replace GF Line transition segments in Fig.5, and the position oscillations during the circle shape motion entry/exit are effectively reduced.

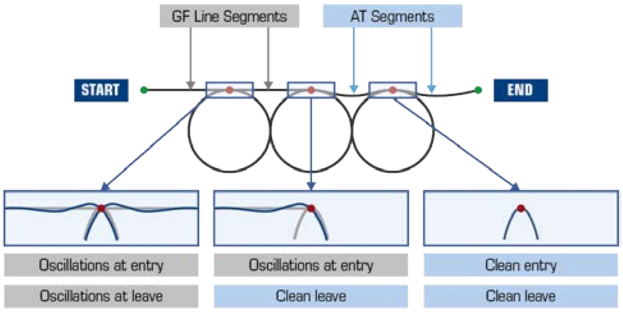


Fig.5 Comparison between IMP Geometry Fitting Line for transition and IMP Automatic Transition.

During the transition motion, no tool process on the target needs to be done. IMP assumes the same and automatically calculates the optimized transition depending on the next shape to come.

In sum, expected tracking error will intensify as the motion kinematic requirements (speed, acceleration, and jerk) increase. While the conventional line transition between shapes could work in some low speed/acceleration cases, there is a risk to force the real-world motion system to its motor and/or mechanical limit of capacity, which could lead to:

- System failure, such as overcurrent in motor during the trajectory transition.
- Bad quality of product: caused by the residual oscillation from the violent transition path when entering the next shape trajectory.

Fig.6a, 6b, and 6c show the different intensity of tracking error on the tool point (theoretical position vs. effective tool point position) of non-stop shape motions in a two-dimensional workspace. The tangential speed during Shape1 and Shape2 - which is the speed along the trajectory - is assumed to be constant in these figures.

Fig. 6a shows that both the shape and transition are made of non-stop line segments. The expected tracking error intensity is represented as red circles at the entry/exit of the shape motions.

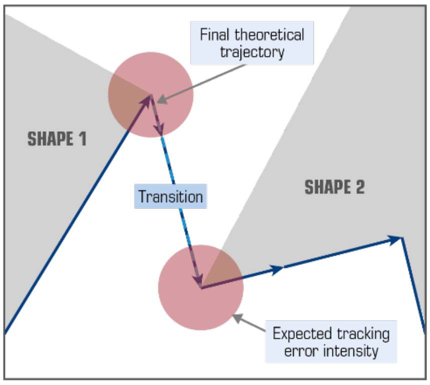

Final theoretical trajectory
SHAPE 1
Transition
SHAPE 2
Expected tracking error intensity

Fig.6a Conventional geometric-fitting lines are used for the transition motion from Shape1 to Shape2.

The size of each red circle is in proportion to the change of the motion vector direction. That is to say, the size of the circle implies the expected intensity of position tracking error at entering/exiting the shape trajectories.

In Fig. 6b, the transition segments are replaced with IMP GF line segments. This allows IMP users to set the geometric fitting error tolerance (green tunnel) and to review the level of expected tracking error before executing the whole trajectory. The error tolerance also helps the IMP to reach the maximum reference speed during the motion. However, the shape entry/exit error level is still affected by the connected transition segment path. In the worst case, the trajectory compilation fails due to exceeding the error tolerance.

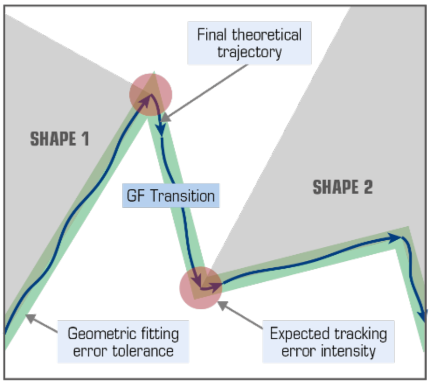

Final theoretical trajectory
SHAPE 1
GF Transition
SHAPE 2
Geometric fitting error tolerance
Expected tracking error intensity

Fig.6b. IMP GF line.

Fig. 6c shows the best trajectory planning example, by interconnecting the shape segments with AT segments instead of GF lines. The AT automatically adjusts the transition path and kinematic profile between the shapes, and this can significantly reduce tracking error during the shape motion entry/exit as result. The expected tracking error is minimum because the AT optimizes the shape exit and entry motions even before the whole trajectory is executed.

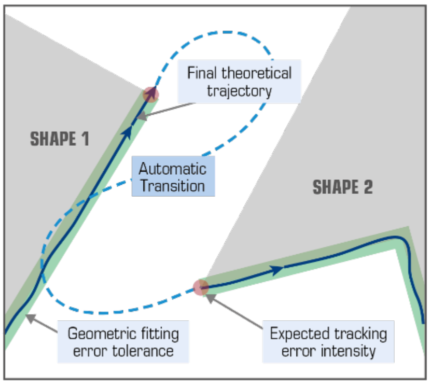

Final theoretical trajectory
SHAPE 1
Automatic Transition
SHAPE 2
Geometric fitting error tolerance
Expected tracking error intensity

Fig.6c. IMP Automatic Transition.

Constant speed is not required during the transition, so AT segment, so it is automatically optimized by IMP for the best result.

Compilation and evaluation of compiled IMP trajectory

The compilation of IMP trajectory will only succeed if the trajectory is designed correctly and feasibly. In addition, the quality of the successfully compiled trajectory can be evaluated thanks to various essential evaluation functions that are included in the IMP library.

Depending on the geometry, the distances and the kinematics values that have been defined, the trajectory might not always be possible. The recommended action when the trajectory compilation fails is to try again by modifying the trajectory with a more reasonable motion planning.

While totally optional, the access to IMP evaluation feature saves time and effort to determine the acceptability of the trajectory, by allowing the whole trajectory evaluation to be performed without any real-world motion system to be connected.

Finally, the compiled trajectory can be saved when necessary, which enables to load and execute the best known trajectory without compiling it again every time.

Multi-axis motion trajectory

Example of 3D multiple circle trajectory

By applying the interpolated motion planning techniques, high-quality theoretical 3D trajectory, ready for execution, can be build. First of all, a basic concept of target motion process has to be developed. As mentioned in the previous chapters, the motion process consists of shapes, transitions, and optionally, events. Fig.7 shows the process of adding translated motion shape and transition segments into an IMP trajectory in sequence.

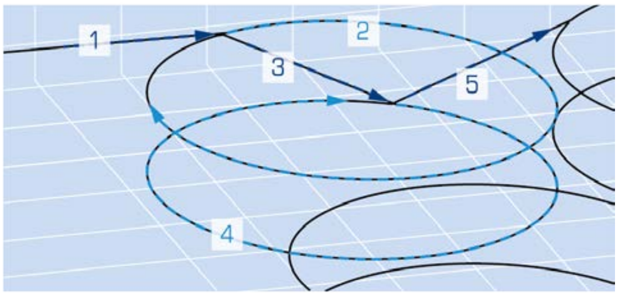


Fig.7 Translating a concept to XYZ circle motion trajectory (Dark blue segment: Transition, Light blue segment: Shape).

Fig.8 depicts a repeating circle shape plan in 3D (XYZ) coordinates. The black path is the theoretical path plan, and the blue path is the actual motion path, which tries to follow the black path. Generally speaking, the smoothness of transition will dictate how much theoretical vs. tool point tracking error occurs.

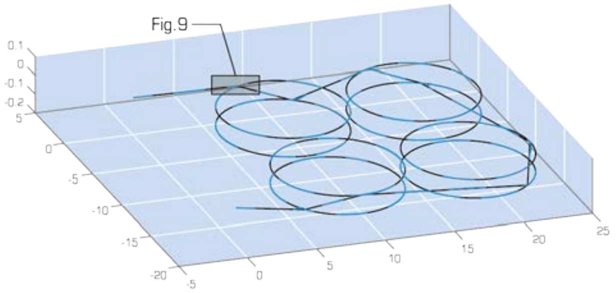


Fig.8 Transition done with G-code line (Black trajectory: Theoretical, Blue trajectory: Tool point).

The black path is not a smooth trajectory, and by taking a closer look at the blue path, the consequence becomes clear. Fig.9 shows where the trajectory transition is entering/exiting the circle shape, and the XYZ tracking error is affecting the tool point trajectory correctness of the circle shape.

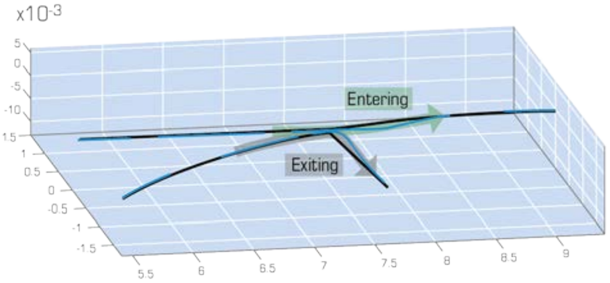


Fig.9 Result of non-smooth transition to circle shape entering/exiting (transition done with G-code line).

Using IMP can improve the trajectory correctness during the shape path, ultimately improving the product quality significantly. The previous trajectory is now reconstructed into IMP trajectory with Automatic Transition (AT) as shown in Fig.10. The complete line transition in the trajectory is replaced with the Automatic Transition segments.

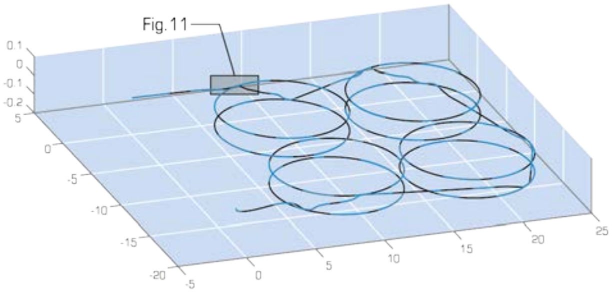


Fig.10 Transition done with IMP Automatic Transition (Black trajectory: Theoretical, Blue trajectory: Tool point).

Zooming into the trajectory transition entering/exiting the circle shape gives a clear evidence of the tool point trajectory correctness improvement with the IMP solution. As shown in Fig.11, the transition path entering/exiting the circle shape does not have tool point tracking error as much as the trajectory using a line transition.

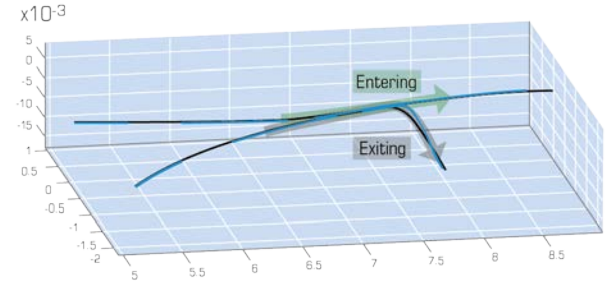


Fig.11 Improved result of smooth transition to circle shape entering/exiting (transition done with IMP Automatic Transition).

If the shape is no longer affected by the oscillation introduced by the transition, the quality and the reliability of the process is increased as well. Ultimately, this example shows the benefits from the perspective of XYZ tool point measurement.

Performance comparaison (G-code vs. IMP)

The example used XYZ trajectory with four cylinder shape patterns.

- The shape diameter: 9mm
- The shape thickness: 0.1mm.

Both G-code and IMP (GF+AT segments) are executing the trajectory for comparison. The position tracking errors of XY axes at tool center point are measured (*) as follows:

- X (Fig.12):
  G-code: ±125 µm → IMP: ±30 µm
  Improvement ratio of IMP: +76%
- Y (Fig.13):
  G-code: ±200 µm → IMP: ±35 µm
  Improvement ratio of IMP: +82.5%

(*) Tool point measurements are performed using HEIDENHAIN grid encoders.

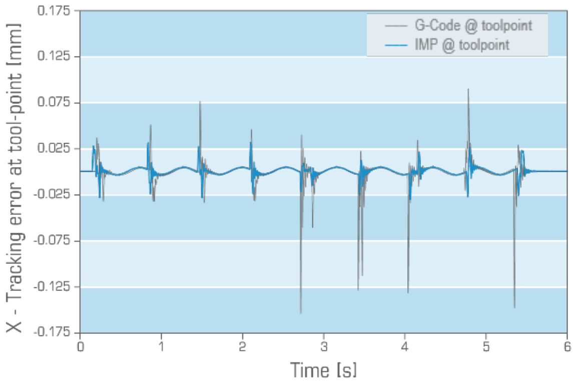


Fig.12 G-code vs IMP (Same motion profile): X tracking error @ tool point.

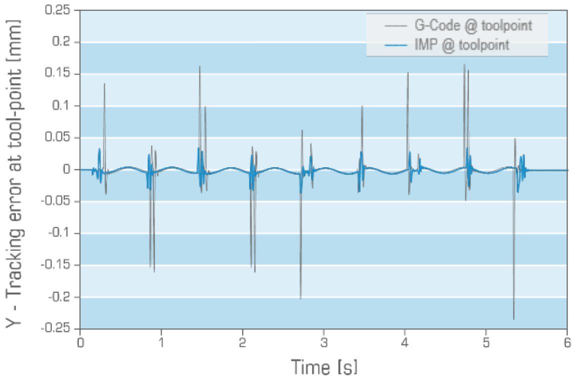


Fig.13 G-code vs IMP (Same motion profile): Y tracking error @ tool point.

The granite displacement is also measured at the same time with granite XY position sensor, and shows that the machine vibration level with IMP trajectory execution is 3-time lower than the G-code one.

In addition, another comparison is done, focusing on the throughput performance. When the maximum kinematic limits are doubled, the IMP trajectory is able to significantly improve the shape pattern execution time when compared to the G-code one, while maintaining almost same level of tracking error.

- Pattern execution time:
  G-code: 5.75 sec → IMP: 2.94 sec
  Improvement ratio of IMP: +48.8%
- Displacement and tracking error comparison of X axis is shown respectively in Fig.14 and Fig.15.

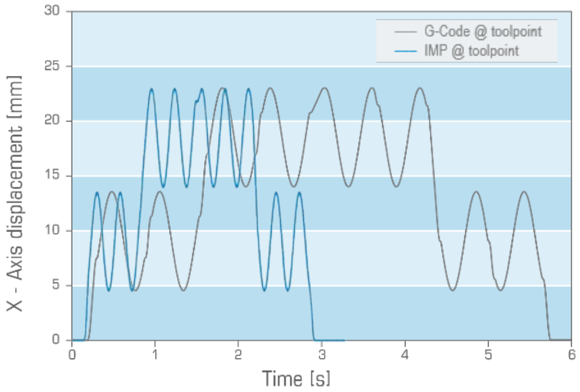


Fig.14 G-code vs IMP (max. kinematic limits doubled for IMP): X displacement @ tool point.

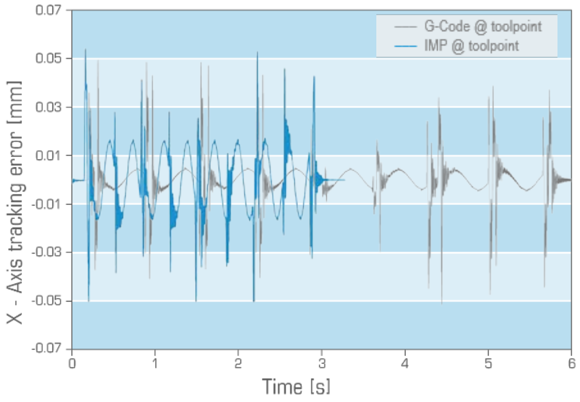


Fig.15 G-code vs IMP (max. kinematic limits doubled for IMP): X tracking error @ tool point.

Analysis

Table 1 shows the general comparison results between the geometric fitting only trajectory and the IMP trajectory with Automatic Transition as it can be observed in the 3D trajectory planning example in the previous section.

Solution	Geometric fitting only	Smooth path + Automatic Transition (IMP)
Transition path total distance	Shorter	Longer
Shape Entry/Exit oscillation	Bigger	Smaller
Event management compatibility	Pre-configured 1D/2D trigger (max. 512) Continuous 1D/2D trigger (unlimited)	Smart 1D/2D trigger (unlimited)
Total motion time	Same	Decreased

Table 1 Comparison between IMP Geometry Fitting vs IMP Automatic Transition.

Analyzing the result of this comparison brings up an interesting point to all potential IMP users: with IMP library, you have the opportunity to increase productivity by switching from geometric-fitting-only trajectory to IMP trajectory. This is because IMP solution can execute fast motion with high kinematic quantities, provided that your trajectory's overall tracking error can be tolerated.

This means that when the tracking error tolerance specification is already satisfied with geometric fitting only trajectory, then motion kinematics of IMP can be increased, so it can process faster while meeting the tracking error tolerance as before. The result is a faster processing while satisfying the motion condition for quality.

Moreover, you can freely simulate the improvement of process using the IMP trajectory compiler, particularly when the outcome is difficult to estimate due to the complexity of the present trajectory (as it is done for the 3D trajectory planning example in the previous chapter).

Implementing multi-axis motion trajectory with IMP

PC application requirements overview

C++ user application with ETEL Device Interface (EDI) and Interpolated Motion Planning (IMP) library generate the complete trajectory ready for execution.

- **EDI**: ETEL Device Interface (EDI) is a set of libraries which enable the communication with the ETEL's controllers, or multi-axis motion controllers, and the access to their functionalities [3].

- **IMP**: Interpolated Motion Planning (IMP) is a Windows-based library working in a PC environment above EDI middleware, which makes the link between the application level and the firmware level.

In addition, IMP is a trajectory generation and execution library optimized for ETEL's products using interpolation features implemented in UltimET and AccurET devices.

- **UltimET light PCI/PCIe, interpolated**: ETEL's motion controller with synchronized and interpolated movement [1].
- **AccurET Modular/VHP**: ETEL's position controller with two axes drive support [2].

These controllers are required to execute a compiled IMP trajectory. The overview of IMP library architecture is shown in Fig.16.

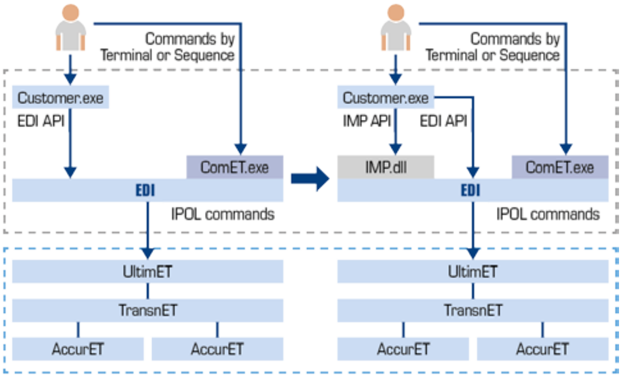


Fig.16 The architecture of IMP library.

PC application design

IMP allows to plan multi-axis synchronized interpolated motion from one to four axes, which allows the implementation of 2D or 3D motion trajectory applications.

An IMP trajectory can easily be constructed with an EDI application by using the IMP functions. To implement IMP, the generic steps are as follows:

1. Create new IMP trajectory (at this point, the trajectory is empty)
2. Define the trajectory bounds
3. Define the 2D trigger constraints
4. Set the first point of the trajectory
5. Add all IMP segment(s)
6. Compile the trajectory
7. Review the compiled trajectory (optional)
8. Save the compiled trajectory (optional)
9. Prepare the ETEL's hardware and execute the trajectory

Once the compiled trajectory is validated, the trajectory may be reused for future executions. The best known trajectory path can be repeated as much as needed. The IMP trajectory does not need to be recompiled again, unless it has to be modified for any reasons.

Conclusion

Compare to the conventional G-code approach, IMP application improve both the precision of motion and the performance of process by making the smooth path over the whole trajectory. When a trajectory includes multiple shapes and transitions, then IMP Automatic Transition is the key feature to improve the quality of the production. The IMP application can be used and deployed in a wide range of applications where multi-axis trajectory calculation is a critical part. Moreover, the possible improvement of the current process can be freely simulated and easily evaluated by using the IMP trajectory compiler. This prove to be a real benefit when the outcome is difficult to estimate due to the complexity of the existing trajectory.

References

[1] UltimET "A motion controller on the TransnET bus" https://www.etel.ch/motion-control/motion-controllers/

[2] AccurET "A modular position controllers" https://www.etel.ch/motion-control/accuret-modular/

[3] EDI "ETEL Device Interface (EDI) library" https://www.etel.ch/motion-control/software/edi-package/

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