

Application note “High accuracy force control”

Keywords:

Contact detection, force control, force ramp, high speed, approach speed, touchdown detection

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

ETEL’s force control feature is specifically designed to maximize throughput and precisely manage the contact force of diverse motion axes. The main benefits are such as: zero stop time, sensorless capability, and precise force control in sub-Newton range.

The force control algorithm developed by ETEL S.A. uses the AccurET computation power to allow fast and smooth transition from position to force control. The landing behavior is controlled to prevent overshoot while maintaining maximum dynamics.

Force control feature

Thanks to a single and simple high level command, ETEL’s AccurET force control algorithm generates:

- Fast approach move,
- Zero stop time from position to force control,
- Automatic contact detection,
- Force overshoot control,
- Robust control toward changing substrate position uncertainty.

Force control is designed to reach sub-Newton accuracy with or without force sensor integrated.

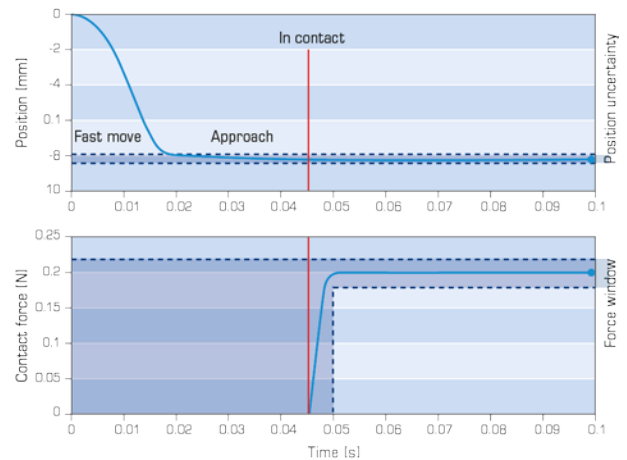


Fig.1 Force control overview.

Zero stop time from position to force control

As the exact contact position is unpredictable, the force control uses an approach phase in which the contact can happen at any time. This approach phase is made at a user-defined constant speed. The speed has a direct impact on the force overshoot at touchdown.

$$F_{overshoot} \propto \frac{1}{2} m \cdot v^2 \quad (1)$$

The switch from high speed to approach speed is defined by a position given by the user depending on the uncertainty of substrate position in the given process. Fig.2 shows the measured profile of the phase switch from high speed (>100 mm/s) to 35 mm/s at approximately 3.3 mm above the substrate. Force control allows to not stop between the two different dynamic segments.

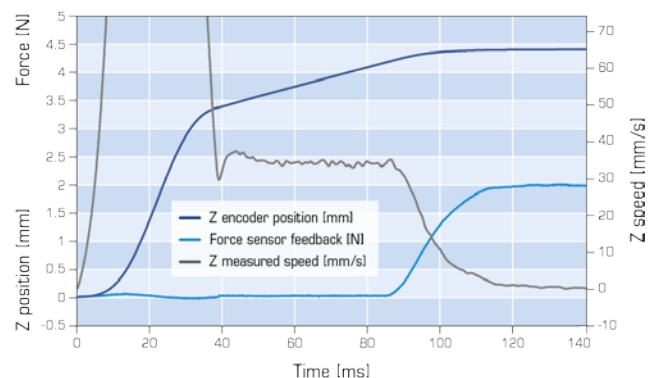


Fig.2 Fast move to approach speed transition.

The measured speed on the Fig.2 shows a quick stabilization of approach speed (few ms). The axis is capable of detecting a surface immediately after switching to approach speed.

Automatic contact detection

The contact detection is defined with a threshold which can be set either on force, or on speed.

On Fig.3, the upper graph shows a contact detection on a force threshold of 0.01 N for a 0.1 N force target. The detection flag is internally used by ETEL's AccurET to control the force overshoot. The flag is available for user application to notify when a touchdown happened.

On the lower graph of Fig.3, the detection is made on the axis measured speed. Approach speed is 11 mm/s with a speed threshold set to 9 mm/s. Detection on speed may be advisable:

- In case the force feedback signal is too noisy to detect an early touchdown.
- If the force feedback signal is filtered (low pass filter). In such a case, the signal is delayed and thus the contact surface missed. The contact on speed allows to get a faster reaction by neglecting the filter delay.

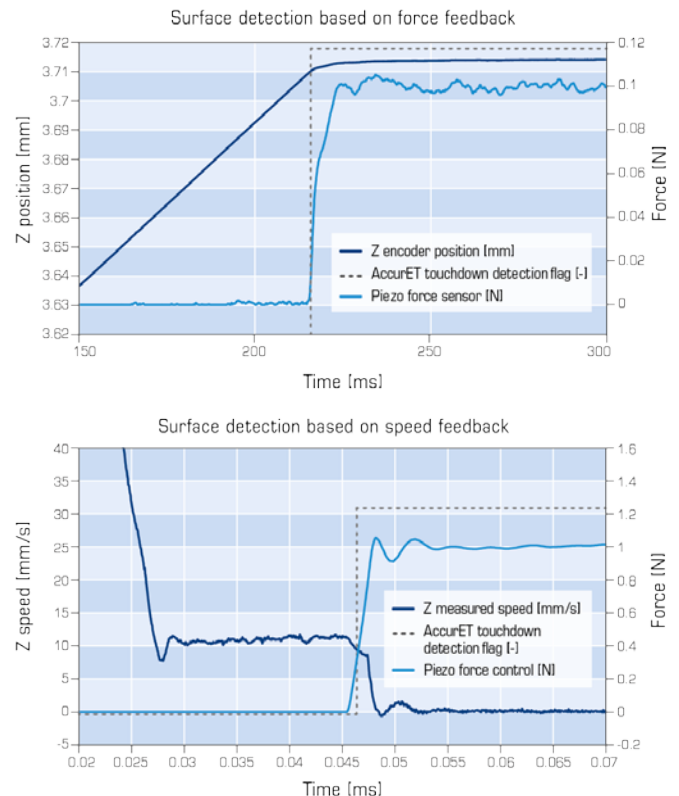


Fig.3 Force control surface detection.

Very fast move and force settle time

Since there is no stop of motion between the fast approach and the landing phase combined with the automatic touchdown detection, ETEL's force control offers a very fast "move & force settle time". Fig.4 shows a 5 N touchdown with a 7.2 mm stroke fast move and ~200 μm approach motion. The contact materials are hard plastic (on the actuator side) and stainless steel (on the contact surface side). A piezo force sensor is mounted in series with the actuator only to validate the force estimator performance.

The 5 N are reached 25 ms after the move starts, within a ±1.8% force window.

The force rise time is 12 ms, 1.8% force overshoot can be observed.

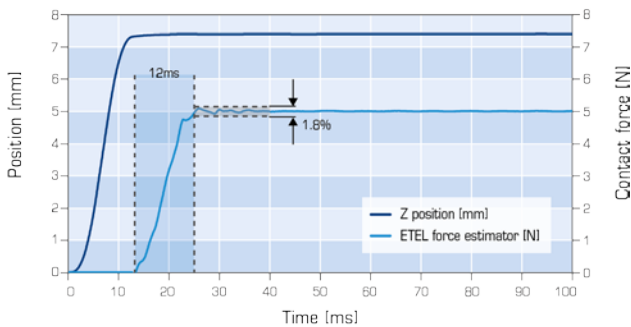


Fig.4 Move & force settle time (5 N touchdown - 7.2 mm stroke).

Force trajectory generation

Once in contact with a surface, force control offers force set point generator function called “force ramp”. A simple high level function can define the new level of force in Newton (or Nm for rotary application) that must be reached in a defined ramp time in seconds. The force transition is controlled and smooth. The ramp trajectory can optionally be smoothed by a FIR filter.

The advantage of the force ramp is to change from one level of force to another as fast as possible, but with an overshoot control. As the contact force is changing, the mechanical frequency response of the full system is changing as well. The ramp avoids exciting these mechanical modes.

Fig.5 is a typical example of the benefit to control the force transition between different force levels. The same actuator is used for this measurement. The upper graph shows an instantaneous force set point change where a mechanical mode is strongly excited (several hundred Hz).

A step response contain many frequencies that excite the system. Using a profiled force ramp, the frequencies contribution can be controlled.

On the lower graph, the force is applied through a 5 ms ramp (low contribution of the mechanical mode frequency component). Using this 5 ms force ramp, the mechanical mode cannot be seen after the ramp finish.

The time lost during the ramp time is compensated by the faster settling time of the force ramp.

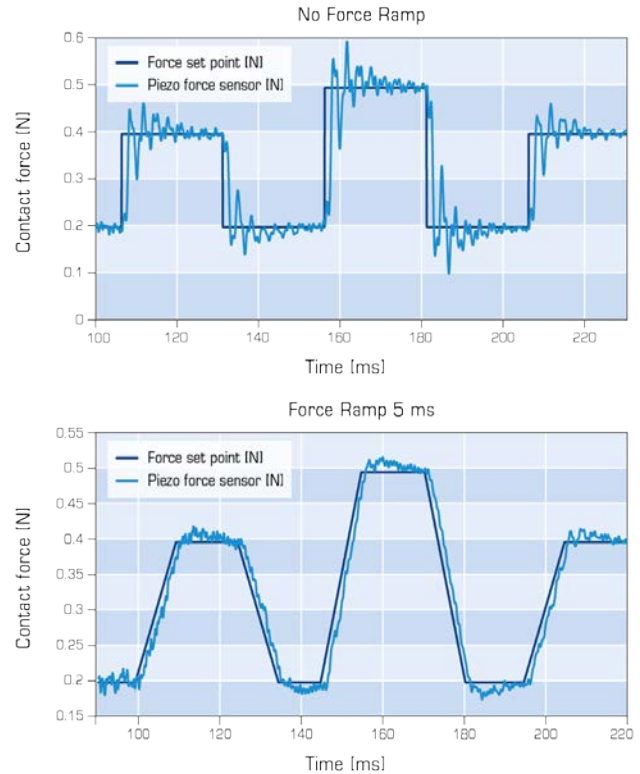


Fig.5 Force ramp smooth control.

“In-window” force detection

Force control feature offers the same “in-window” feature as for the encoder position. A force window around the targeted force can be defined. When the force is within the window during a specific time, a flag is raised by ETEL’s AccurET.

Fig.6 shows a 1 N touchdown. The force window is set at ± 0.01 N during a minimum time of 10 ms. After entering the window, the force signal remains in the window for 10 ms, so the flag raises. This flag can be used in the software application to continue the process.

The benefit of using this force window feature is to continue the process as soon as the target force is reached and stable. Compare to waiting a fix time after the touchdown, the “in-window” feature brings more throughput and force reliability.

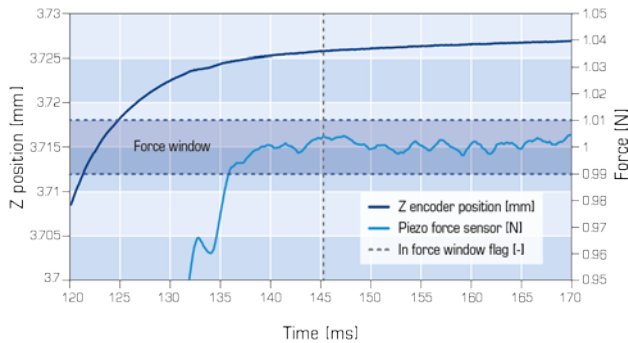


Fig.6 In Force window feature.

Accuracy of the force at tool point

ETEL's force control algorithm has two options for the force feedback:

- Use an external force reference (analog signal, 1Vpp signal, TTL signal, any data from PC...)
- Use ETEL's force estimator (no external force signal needed) to reach the same performance as with a force sensor. This mode needs a specific calibration setup that can be done with the ComET software.

Both options, external force feedback and ETEL's force estimator, can be used to close the loop of the force control.

The sensor less option has the advantage to require almost no re-calibration. Not having to embed a sensor may also improve the control bandwidth, and therefore the performance. However, the force accuracy of this solution depends on the mechanical integration. It usually provides the best results with direct-driven low-friction actuator.

A calibrated force sensor has the advantage to have a certified accuracy on its working range by the sensor provider. The force feedback accuracy and repeatability are not affected by the mechanics of the axis.

Force estimator accuracy

The force estimator model used in ETEL's AccurET is designed to fit the contact force at actuator tool point. To be able to compute this force, the controller

is taking many physical variable inputs, leading to an excellent simulation of the force.

During the critical phase of the surface touchdown, we can often observe a force rebound and a bouncing effect.

As shown in the Fig.7, the force estimator is able to simulate the force bouncing even if the axis is already in contact and not moving. A piezo force sensor is mounted in series with the actuator to validate the accuracy of the estimated force.

The capability of such an accurate force estimation allows the user to control and damp the potential force oscillation and force variation to ensure a perfect contact.

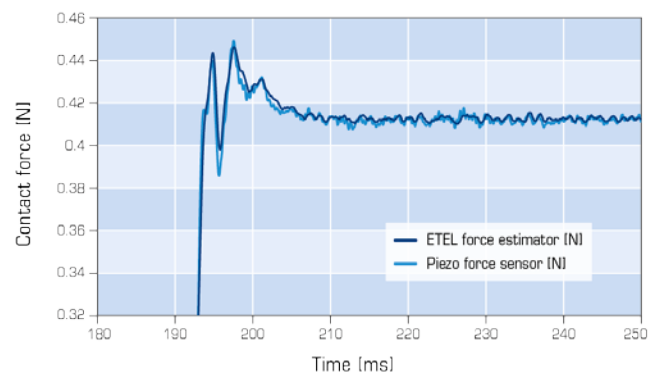


Fig.7 Force estimator accuracy.

The force estimator is not only accurate at one specific location. If the touchdown position is changing by few micrometers or even millimeters, the force applied at tool point remains accurate.

Several applications require different touchdown positions. For example, if the force is applied on different contact stiffnesses, the compression factor will change and thus the contact position will vary.

Fig.8 shows the same actuator applying 1 N contact force at different contact positions. Even when the contact position is detected earlier, the final contact force and the overshoot behavior are the same (here validated by a piezo force sensor in series with the actuator).

Thanks to this capability, the application software does not need to manage different set point

commands depending on the precise touchdown position.

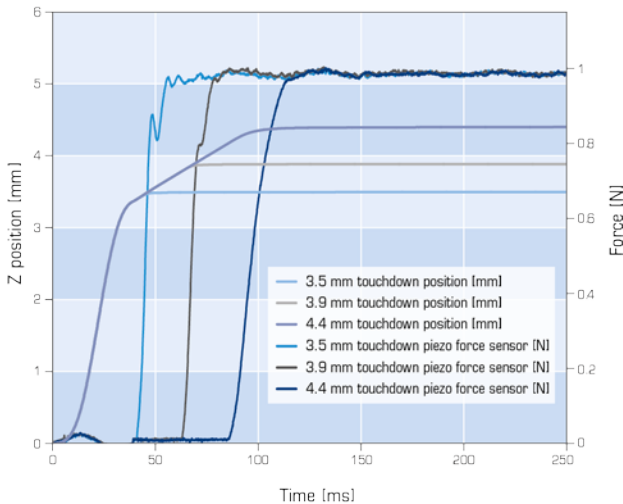


Fig.8 Force estimator accuracy at different actuator heights.

Every external force that varies with actuator position (such as spring in series, cables, gravity compensation, etc.) can be taken into account by the ETEL's force estimator.

Force estimator repeatability

Many force feedback sensors are affected by force drift over time (like piezo force sensors). Non-linearity of sensors has negative impact on the force repeatability.

ETEL's force estimator has a proven repeatability as shown in Fig.9 with a touchscreen force calibration application. Two measurements are taken, the first one at production first touchdown, and the second one after 440'000 touchdowns (7 days of continuous production). For each measurement, the mean force is issued from 2'500 points computed every 0.4 ms.

Measurement#1 (at 1st cycle): 0.4964 N

Measurement#2 (after 7days): 0.5071 N

This leads to the following error factor for the force repeatability:

$$\begin{aligned} \epsilon_F &= \frac{\Delta\text{Force}}{\text{nominal force}} \\ &= \frac{(0.5071-0.4964)}{0.5} = 2.14\% \quad (2) \end{aligned}$$

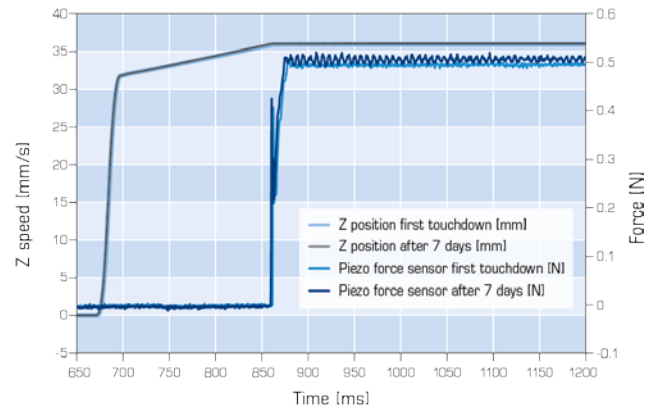


Fig.9 Force estimator repeatability over time.

Note that the force repeatability is affected by the axis mechanics. So when the mechanics is not repeatable, the force estimator is also impacted.

To ensure force estimator accuracy, ETEL S.A. provides software tools to calibrate the estimator. This accuracy can be calibrated during manufacturing, or after an actuator maintenance service.

Force control in application

ETEL's AccurET force control feature is already widely used in the industry for operations like:

- Wire bonding.
- Die bonding.
- Component testing, calibration or placement.

Fig.10 shows a touch-screen calibration process. The calibration is done at each corner of the screen and at its center. For each of the five points of interest (POI), a force of 0.5 N, 1 N, 2 N, 5 N and 10 N is applied during 1 second (after entry in the force window of $\pm 2\%$). The specifications meet during this process are an overshoot smaller than 0.1 N and the total travel before touchdown around 8 mm.

Fig.10 also shows that the contact height is different for every contact point.

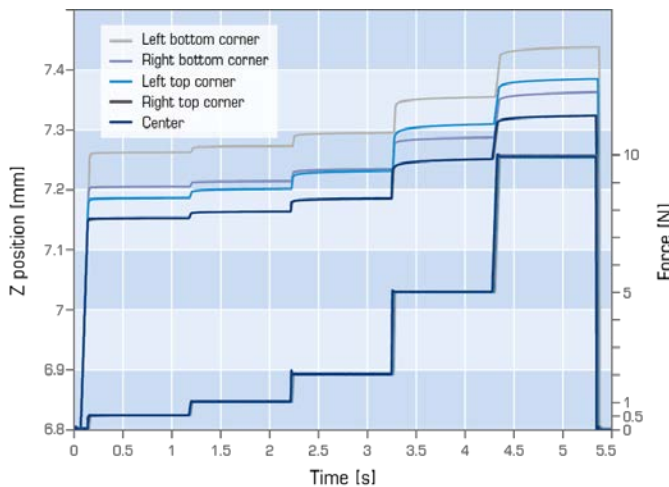


Fig.10 Force control in industry.

During this process, the cycle time is measured at 26.965 seconds per screen (including 25 seconds of measurement). Which means that only 400 ms are needed for a complete cycle at one calibration location, as follows:

$$T_c = \frac{(26.965 - 25)}{5 \text{ POI}} \sim 400 \text{ ms} \quad (3)$$

The throughput of screens tested per hour reached 133.5 UPH.

Using sensor less mode, the force accuracy is still better than 2% of nominal force for all the 5 locations (controlled with external piezo force sensor) after 22'400 screen calibrations.

Conclusion

Since ETEL S.A began to develop AccurET force control, the algorithms and features have been continuously improved to become a complete, stable and efficient solution. This software maturity is also reached thanks to many application types, developed for various industry sectors.

As illustrated in this document, AccurET force control is able to increase throughput without ever compromising accuracy. Using the unique sensorless force estimator is a cost effective way to replace a force sensor, with the same level of performance.

References

- [1] AccurET "A modular position controllers" <https://www.etel.ch/motion-control/accuret-modular/>
- [2] ComET "Commissioning tool" <https://www.etel.ch/motion-control/software/comet-software/>

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