Application note
"ETEL Advanced Motion Control for Wire bonding"

Keywords:
Interconnection, Bonding, Integrated Circuits, Light Emitting Diode (LED), Transducer, Capillary, Die attach, Wedge, Electrical Flame-Off (EFO), Ultrasonic, Free-air-ball (FAB), motion control, encoder, QFN, SiP, Loop trajectory, library, Real-Time control.

Abstract

This application note describes the LED/IC wire bonder ecosystem (market drivers, architectures, timings…) and focus specifically on the main technical challenges for the motion control part. The selection of the control architecture and its position encoders have a significant contribution on the total machine performance. Dedicated motion control solution from ETEL, as well as position encoders from HEIDENHAIN can greatly help wire bonder designers to face the new market requirements derived from chip miniaturization and its enhanced complexity.

Introduction

Among the different equipment used in the semiconductor industry for mass production of Integrated Circuits (IC) and Light Emitting Diodes (LEDs), wire bonders are probably one of the most challenging in terms of motion control management. A first explanation relies on the fact that this technique is one of the oldest used in the semiconductor world with already many years of intensive optimizations (wire bonding was first reported in 1957). In addition, its short cycle times, complex looping trajectories and ultra-low impact forces (~30 grams) are calling for the most advanced control strategy. Today, market calls for continuous miniaturization and cost reduction in the whole IC assembly supply chain, which translates into smaller pad pitches, higher positioning accuracy for the tip, higher throughput and better impact control when the capillary tool tip contacts the pad or lead. Despite these complex challenges, the industry succeeded in offering good bond quality at increased bond rates (up to 20 wires/sec), maintaining wire bonding as the lowest-cost and the most reliable and flexible interconnection method. With more than 30'000 wire bonders sold every year worldwide, the market is nowadays extremely competitive, pushing the prices down to a level which may jeopardize OEM equipment makers to invest in R&D resources to work on machine redesign and motion control improvements.

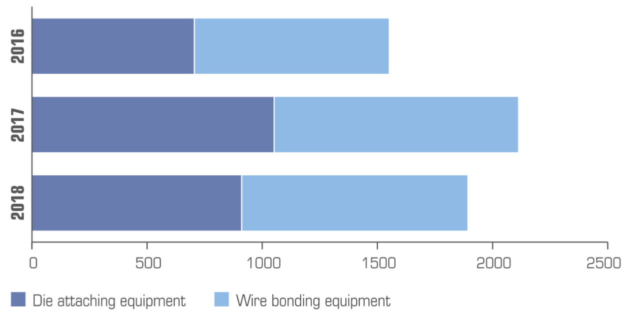

Fig 1: split of Equipment sales in the bonding industry (VLSI April 2019).

ETEL, with more than 30 years of expertise in the design of controllers and multi-axis systems for the semiconductor industry, is particularly well-positioned to provide to wire bonder manufacturers proven and dedicated electronics solutions, from hardware products to software tools.

Wire bonding, a leading interconnect solution.

Competing with die attach techniques

Chip-to-substrate interconnections provide the electrical paths for power and signal distribution. These interconnections are made either by die attach (die bonding, flip-chip) and/or wire bonding techniques. Although die-attach applications are growing faster, wire bonding continues to produce around half of interconnects in the IC world, driven by Memory ICs, QFN, leadframe packages, System in Packages (SiP) and LED packages.

Process steps

Wire bonding is the process in which a die and a lead frame (or substrate) are connected together using very fine diameter wire, typically made of gold. The energy input for the soldering process is a combination of force, temperature and/or ultrasound.

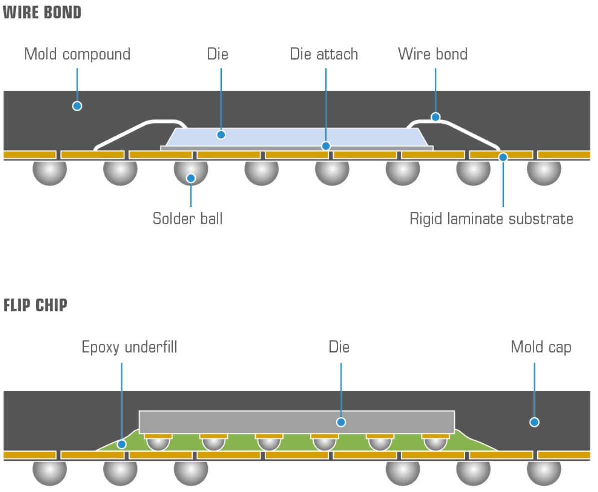

Fig 2: Differences between wire bonding and flip-chip die attach technique.

The two main wire bonding process technologies are wedge-wedge and ball-stitch bonding. The difference relies on the bond shape which is determined by different bonding tool used (a wedge or a capillary tool). The ball-stitch bond process is by far the most commonly used interconnection method in integrated circuit packaging (> 90 %), using gold or copper wires. In this process, the wire is fed through a ceramic capillary and an electrical flame-off (EFO) melts the wire and forms a sphere, called free air ball (FAB) at the end of the wire. The free air ball is then pulled up to the tip of the capillary and the tool moves laterally to the first bond location, typically on the die itself. The tool presses the free air ball under a controlled force. A looping motion is then programmed according to package geometry to bring the wire to the second bond location, typically on the substrate pads. Again force, ultrasonic and heat energy create the connection between the wire and the pad. The wire is then torn off by closing the wire clamp, moving the tool straight up.

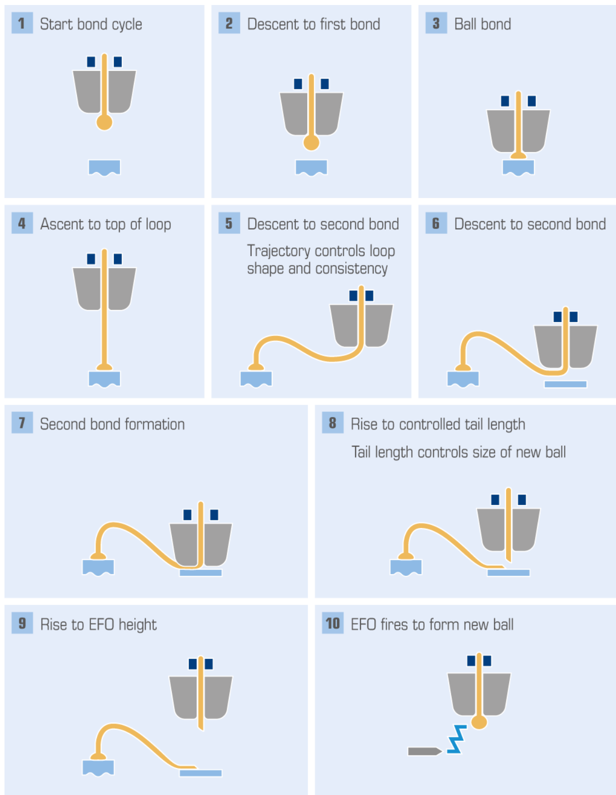

Fig 3: Main process steps for ball bonding

Recent adoption of copper wire bonding opening new Motion Control challenges.

Over the past 10 years, one of the major process improvements deployed in the field was the replacement of gold with copper wires. This new technology offers better performance and is more economical than traditional gold wire bonding. Despite the fact that copper is traditionally the metal of first choice used for power and communications, in wire bonding, gold has been originally selected as the best candidate for ultra-fine interconnections, because it is easy to work, soft and resistant to oxidation. Nevertheless, gold electrical and thermal conductivity are not as good as copper and the temptation to move to copper came quickly on the table as an "easy" way for improving IC's thermal behavior and data bandwidth. However, despite the obvious cost & performance advantages, there were many challenges in developing copper wire bonding: the main one being probably its fragility, higher hardness and brittleness relative to gold. This particular aspect typically raised up the technical requirements on the motion control side. Indeed, this results in a harder free air ball (FAB) formed at process start and higher risks of pad damage at touchdown. Conclusion: the adoption of copper wires cannot be done without the emergence of new generation of wire bonder with new force control capabilities…obviously without impacting machine thoughput. ETEL's unique capabilities in force control will be covered in the next pages but this example shows how motion control optimization keeps running, highlighting how important it is for wire bonder designers to engage with a supplier who is capable of anticipating semiconductor evolution trends.

Wire bonder mechanical architecture, a compact and stiff design.

The most common wire bonders used in semiconductor industry consist of a three-axis system with a bond head (Z) coupled to an X-Y stage (flying bond head type). The X and Y axes are moving the bond head either to realize the bond itself or to move to the new bond starting position. Typically, for semiconductor substrates loaded in strip format, an X-Y moving area of 100 mm per 60 mm is observed. For other processes requiring larger bond areas, alternative concepts are used with a fixed bond head and a movable substrate offering larger strokes but at a cost of lower throughput (hybrid bonders).

The best wire bonding machines used in the semiconductor industry can bond between 15 to 20 wires/sec. These need really fast moves and short settling times for the three axes. For X-Y, it represents a 1 mm move without overshoot within ten milliseconds for an acceleration between 15 and 20 g. This is only possible with highly stiff axes with low moving masses, sliding on advanced bearing technology. It is then not a surprise to see that carbon fiber is often used to build these axes.

The third main axis, Z, is controlling the bond itself and is probably the most challenging in terms of motion control. It is not purely a Z motion as the transducer arm is actuated by a rotary Z voice coil motor. Thus, for each bond, an interpolation with XY axes is needed to realize a pure Z motion relative to the substrate.

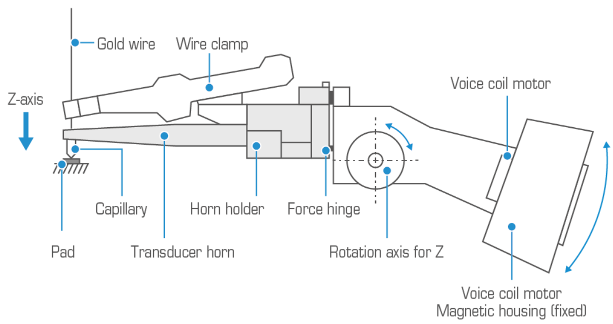

Fig 4: Schematic of a typical bond head mechanical design.

This rotary motion is guided by a flexure that cancels the friction forces. The rest of the bonding head assembly consists of a very thin and fragile capillary to guide the wire, an ultrasonic transducer used to solder the wire to the substrate, and a wire clamp to apply tension or cut the wire. The main challenge of this assembly is to satisfy the very demanding motion control performance. Like the X-Y stage, the bonding head design structure must be stiff enough to offer to the controller the possibility (if it is capable technically speaking) to reach minimum current-loop bandwidth of typically 1.2 kHz (> 3 kHz have been demonstrated using ETEL) and a position-loop bandwidth of around 300 Hz (> 400 Hz have been demonstrated by ETEL) to reach the state of the art performance.

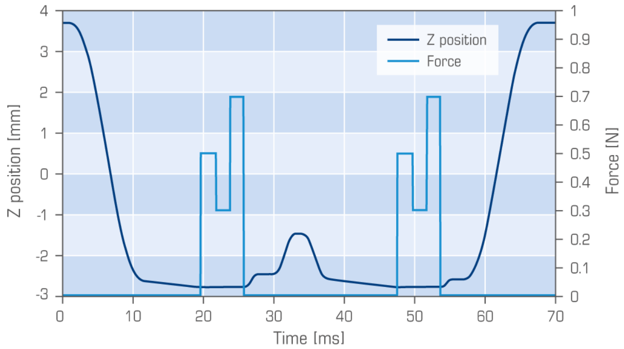

Fig 5: Typical Z motion profile (in blue) with its two touchdowns and wire trajectory loop. Applied force is represented in light blue.

On top of this, the Z axis also requires soft touch contacting capabilities, a high trajectory fidelity and be able to run multiple interactions with the EFO, wire-clamp, and acoustic transducer. So, having all these requirements running smoothly all together can be only achieved if two conditions are fulfilled: the first one relies on a smart, robust and stiff Z mechanical design, and the second calls on the association of a high-level controller, capable of actuating this highly stiff mechanics with a high control-loop bandwidth, in order to follow the trajectory required by the process within the desired cycle time.

HEIDENHAIN exposed linear encoders for X, Y and Z axes.

On X and Y, the challenge is not only to perform a high-dynamic move between each bond but also on keeping the planned trajectory of the wire that is being unwound. A tracking error of 10 µm is typically asked while acceleration and speed reaches respectively 20 g and 0.85 m/s. This can be only made with a robust and thermally stable encoder.

The LIF series from HEIDENHAIN is particularly well-fitted to play this role. On the Z axis, which follows dynamics that are even higher than X and Y (up to 120 g of acceleration), an optimal trajectory fidelity with high frequency of positions acquisitions translate into the use of a high resolution encoder. HEIDENHAIN here typically recommends the use of its ERP 1000 series of rotary encoders adapted to the stroke of the rotary voice-call used in wire bonding. Several models are available with a grating up to 63’000 lines per turn with ± 0.9” accuracy of graduation.

These high accelerations/decelerations within short distances are literally maltreating the mechanics, generating vibrations and high mechanical constraints on all elements, quite often in a dusty environment. Component reliability and sensitivity to contamination are of utmost importance and that’s another reason to use HEIDENHAIN encoders for this application: they have large mounting tolerances (meaning that the signal is acquired through a very robust manner), are insensitive to contamination and known to be highly reliable over time.

Fig 6: ERP 1080 rotary encoder with its scale and its scanning head.

ETEL motion control solution for X, Y and Z axes

ETEL’s AccurET product family allows to connect and synchronize the different axes from the machine, namely X, Y, Z and potentially other auxiliary axes like the wire clamp motor to get advantage of the dual-axis offered by each ETEL controller. Its architecture is made of several layers to ease customer in all aspects of its machine control design from position controller to dedicated DLL library and powerful commissioning software.

Fig. 7 AccurET position controllers family

In wire-bonding market, the need for high speed control, combined to a multitude of actions to be executed in the millisecond range along the bonding cycles drove most of designers to use real-time operating systems for their wire bonding architecture. Traditional operating system (OS) are responsible for managing the hardware resources and hosting applications that run on the computer. A real-time OS does the same but is also specially designed to run applications with very precise and reliable timings. This is typically what is required in a wire bonding machine: deterministic event responses and continuous trajectory feed are key to running the process. Indeed, one bonding cycle includes a big amount of data from the sharing of the trajectory points every 50 µs to the different events which takes place all along the trajectory (EFO spark, open clamp, activate ultrasonic, contact etc.). A perfect determinism of each communicated data is mandatory to ensure a fast, reliable and smooth bonding.

This is the reason why ETEL designed a suite of software products running on RTX, a real-time OS working on a Windows machine:

- The ETEL EDI standard library running on RTX.
- A dedicated application programming interface called “Wire Bonding Planning”.

These software libraries are associated to a standard ETEL control hardware architecture to complete the ETEL solution for wire bonders:

- ETEL standard UltimET PCIe motion controller.
- ETEL standard AccurET position controllers.
- ETEL TransnET proprietary Bus communication protocol.

Wire bonding critical steps & timings

The critical steps in the wire bonding process aim to achieving reliable bonds, maintaining desired loop and positioning the bonds accurately, all of this to be executed in very short timings.

CRITICAL STEPS	TIME (ms)
From EFO level, start new bond cycle, descent until landing zone (100 um), approach at die	20
Search for contact	
First bond	
Search for surface detection on leadframe	20
Second bond and tail	
Move back to EFO level	7
TOTAL	**67**

Fig. 8 Typical wire bonding process steps and their associated typical timings.

The next chapters introduce the different tools and capabilities offered by ETEL product portfolio to serve wire bonding motion control needs.

AccurET hardware performance

First of all, there is a number of controller hardware characteristics which are essential to be able to answer to the wire bonding market requirements. As examples, the few grams of impact forces that are detected through the variation of current level makes signal to noise ratio (SNR) of the controller a key performance specification (up to 100 dB for AccurET

VHP). Also, the trajectory fidelity when creating the wire loop is of critical importance for bond reliability. In that regard, the high control bandwidth from AccurET allows to follow the desired loop shape with minimum tracking error along the trajectory.

In addition, the ETEL decentralized architecture helps to answer to the extremely short timings required by the wire bonding market. ETEL's strategy is to bring a maximum of computation power and intelligence locally, as close as possible to the application, in order to cut any time latency and unnecessary communication to the main PC. Position and current real-time control algorithms, encoder computations, local mapping compensations, local I/O related programming are directly managed at the position controller level.

Finally, the ETEL TransnET real-time fieldbus with its 1 Gbit rate and "nanosecond jitter" level allows optimal communication between the UltimET motion controller and the AccurET position controllers. Thanks to this TransnET protocol, the UltimET motion controller is capable of handling an interpolated bonding trajectory at 20 kHz, thus bringing each new set point every 50 µs, which is unique on the market.

Wire Bonding Planning API

The ETEL Wire Bonding Planning (WBP) library is intended to guide wire bonder designers in the activation and implementation of all the real-time steps which compose a bonding cycle. It has the following features:

- Set of tools to ease trajectory management (set of trajectory primitives, configurable smoothing capabilities, configurable actions, complying with kinematic constraints).
- Specific force control mode to ensure smooth bond with time optimized transitions.
- Real-time action management (clamp, ultrasonic activation, bond force window tracking etc…).

Ease trajectory management

The shape of the trajectory when forming the loop is of utmost importance in order to fulfill the requirements of the latest generations of integrated circuits. A typical loop trajectory used in wire bonding is illustrated in figure 9. It describes the path of the capillary, thus the wire, to generate the wire joint between the die and the pad. It is composed of several segments which are concatenated and filtered in order to execute a single, smooth and continuous trajectory.

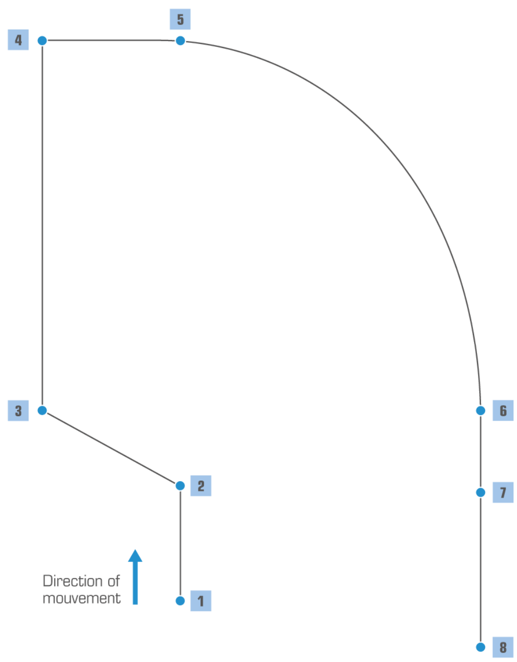

Fig. 9 Typical Q loop trajectory from 1st contact point on the die up to leadframe pad.

The Wire Bonding Planning API has native commands/functions available to ease the construction and execution of this type of trajectory. After having set some initial control points to be included in the trajectory, the user defines some geometrical primitives to define the control shape of the trajectory path. Then, the API applies the kinematic equations to finally compute the full trajectory at a frequency of 20 kHz (one point each 50 µs), smoothening the corners and making sure the acceleration and velocity boundaries conditions are respected.

The trajectory generation is a crucial part of a successful bonding process. Many of the wire bonding equipment manufacturers will decide to rather design their own trajectory, without the help of the native trajectory generation. The ETEL Wire Bonding Planning API also offers top performance to the customers interested in only executing their trajectories, while keeping some functionalities such as coordinate transformation or trajectory smoothing in the API.

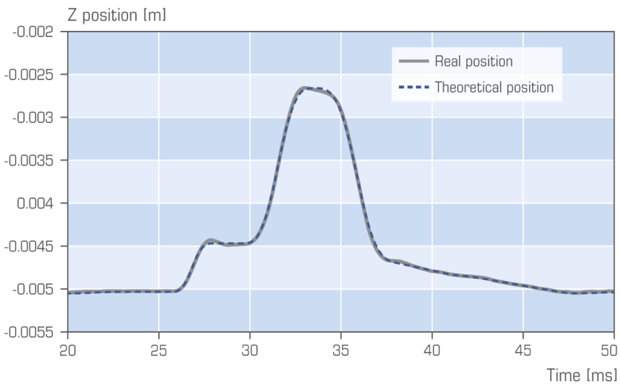

Fig. 10. Theoretical and real Z position during loop trajectory. Typical tracking error with ETEL controller is below ±20 µm, matching IC market requirements (typically ±100 µm for the LED market)

The transitions to force control section are also automatically handled by the library, for example by adding a segment subdivision to adapt landing velocity assuring smooth force control transition. This helps to reach optimal touchdowns minimizing overshoot and force settle time.

Embedded force control algorithm

The force control algorithm enters into the game when the capillary descends to first bond. There are two main steps: a high speed portion and then, close to the work surface, a slower, controlled velocity descent during which the bonder senses contact with the surface. It is not unusual for the height of die to vary by several hundreds of microns. Therefore, a wire bonder must be capable of sensing touchdown for each bond and cannot rely on previous height data, confirming the key contribution of a good force control algorithm in the total time budget of a bonding cycle.

In addition, as the pad pitch decreases, the size of the free air ball (FAB) must also decrease, which degrades the ability to absorb an impact force. Indeed, the impact force is directly related with the squashed ball size in the wire bonding process. If the impact force is too high, the squashed ball becomes larger than the size of the pad, leading to a connection shortcut and some issues with the ultrasonic soldering.

ETEL's force control feature embedded in the position controller is specifically designed to maximize throughput and precisely manages 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.

This ETEL functionality is accessible from the Wire Bonding Planning API through commands directly available in the library (set the force range, window duration, landing velocity…). It is basically made of 4 phases along the bonding cycle: Activation when capillary enters the nominal landing position, landing, touchdown and contact detection when force is stable within defined in-window parameter.

Real-time action management

Actions are sequences of operation triggered at some point of the trajectory execution through the digital outputs/inputs from the controller. Examples are activating the ultrasonic soldering, or receiving the signal that the free air ball is formed.

There are many of these actions along a bonding cycle and the challenge relies on the capability of the controller to execute these actions in time, not to jeopardize the 60 ms of the bonding cycle. For this, the fast I/O embedded in every AccurET are used. They ensure reaction times of a few tens of nanoseconds.

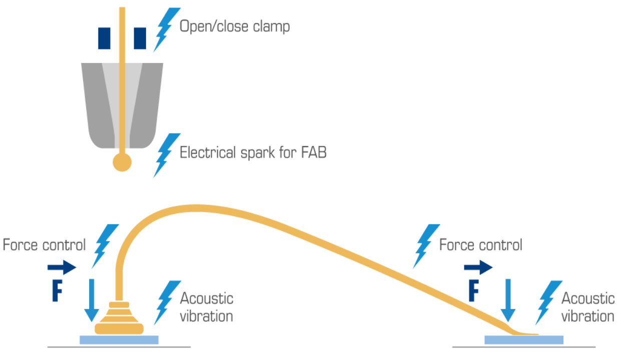

Fig. 11. Illustration of a typical sequence of actions occurring during a bonding cycle.

To do so, commands and communication must be done at very low level in the controller to cut any time latency and activate as fast as possible the hardware inputs/outputs signals.

Pre-programming through specific sequences all these events can become quickly complex and laborious, with many usual PC-to-controller communications.

In order to simplify its management and cut communication latencies, ETEL is using within its WBP library a dedicated functionality called “Real-Time Value” which consists in a continuously sharing of data between all controllers, at each TransnET cycle, meaning each 50 µs, through a specific real time channel. For a defined process sequence, it is then possible to build upfront a matrix of events associated to specific positions, which is then rolled out by the motion controller during the process.

Like this, the different events can be activated automatically, when Real Time Values switch to the desired state, without pre-programming any trigger, saving precious communication time.

ETEL motion system expertise to support customer

In order to cope with many technical challenges, wire bonding manufacturers are looking for a global motion control expertise able to understand the contribution of each parameter which makes the machine performance: controller hardware specifications, role of advanced control features, motor and encoder performance, influence of mechanical design, selection of materials etc… In wire bonding like in all high-dynamics applications, it is a must to look at the interdependence of performance contributors. Indeed, the improvement of the bond head stiffness for example might not result in higher dynamic if the controller is already running at its bandwidth limit.

ETEL, as part of the HEIDENHAIN group, is in position to offer to the market a complete mechatronics expertise, from R&D consultancy to finite element simulations or programming services.

Conclusion

With more than 20 years of experience in the wire bonding market, ETEL and HEIDENHAIN have consolidated over the years a wide range of dedicated solutions, namely on the motion control solution and position encoders. As described in this paper, these components are playing a huge role in the overall machine performances. With its global mechatronic expertise coming from its long experience in the supply of the most advanced motion systems for the semiconductor industry, ETEL is the best partner to accompany any wire bonder manufacturers willing to bring their machine design at the high-end level.

References

- *ETEL application note force control*
- *AccurET product datasheet - https://www.etel.ch/fileadmin/PDF/Products/MotionControl/AccurET_modular_300-data.pdf*
- *"TI's journey to high-volume copper wire bonding production", 2014.*
- *"Advanced control in a high-speed wire bonder, Mikroniek, 2012.*
- *Advanced Packaging, April 2000.*
- *Challenges and Resolution for Copper Wire bonding, Journal of Engineering Research and Reports, 2018.*
- *Wire Bonding Advancement, Nelson Wong, Kulicke&soffa.*

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