# Modelling, design and implementation of a servo-electric plunger mechanism for glass container forming machines

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*Within the scope of increasing the reliability, the controllability and the speed of glass container forming machines and thus improving the related forming process, servo-electric drives are increasingly replacing pneumatically driven mechanisms that still represent the standard in IS machines today. This contribution discusses the design and the results of an experimental unit of a fully functional servo-electric plunger mechanism that has been developed by* Emhart Glass SA. *Since the control of the parison pressing action needs to satisfy a variety of different challenging demands, a thorough understanding of the system is indispensable, and therefore a physical model of the servo-drive and of the glass forming process has been developed. It allows one to simulate the complete system in virtual reality and to iteratively optimise the electromechanical device, as well as the control algorithm. Trials with the experimental unit that has been built based on the theoretical results confirm that the accuracy of the models is remarkable. Extensive field tests were successfully carried out at* Wiegand Glas*, Germany, in a real production environment. The encouraging results demonstrate the high potential regarding reliability, controllability of the forming process, performance and customer benefit of a servo-electric plunger mechanism.*

In order to meet the increasing demands of modern glass container forming machines, a clear trend in today's industry shows that traditional pneumatic actuation solutions are increasingly replaced by servo-electric drives. A few examples of this trend are *Emhart Glass*' servo-electric invert mechanisms, servo-electric take-outs, servo-pushers, or even the new servo-electric NIS machine[(1)] with nine servo-electric axes per section. At a first glance, it seems surprising that in spite of this trend the *one* mechanism that is directly involved in the glass forming process – the plunger mechanism – is still not available as a servo-electric solution on the market. One reason for this situation is that a servo-electric plunger poses some considerable technical challenges. Many attempts throughout the world have been made to overcome these challenges, but up to now all have failed either for technical reasons or because they did not provide sufficient customer benefits.

Emhart Glass has committed itself to meeting these challenges and has developed a fully functional experimental unit of a servo-electric plunger mechanism. The main objectives were to demonstrate the technical feasibility by means of field trials, to develop appropriate control algorithms, and to explore the potential for process improvement, reliability and added customer value. The challenges to overcome and the main results of that study are presented in the following paragraphs.

## System requirements

### *General*

Even if the realised experimental unit cannot be considered as prototype of a product, the demonstration of feasibility requires that the test setup satisfies the substantial constraints given by existing machines. The significant boundary conditions are: mechanical retrocompatibility, usability of the existing plunger and positioner equipment, the possibility of cooling the plunger through a conventional cooling tube in the centre and the possibility of connecting the servo control system to a standard timing system. Furthermore, it is mandatory that the servo-electric plunger can be run not only in PB and NNPB-processes, but also in BB-mode.

### *Control system requirements*

In contrast to most electric servo drives where the *one* major goal is to have a mechanism follow a well-defined motion trajectory as precisely as possible, the requirements of a servo-electric plunger are more complex. Since a plunger pressing cycle consists of several phases, each of which demands completely different characteristics from the controller, advanced control concepts need to be applied. When pressing the plunger into the glass, for example, it is not tolerable to simply

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drive it to a defined target position. Since the end stroke varies from cycle to cycle with the volume of each gob and also from one cavity to another, unfilled finishes or overpressing would be inevitable. It is rather a question of driving the plunger into the glass with a well-defined force, of guaranteeing a quick and reliable moulding and of keeping the blank mould opening forces below the clamping forces. This strategy also implies that changes in the glass viscosity or varying mechanical friction can be compensated for. When retracting the plunger out of the formed parison, however, the main difficulty is to overcome the strong stick–slip effects and to ensure a smooth acceleration downwards; jerky plunger movements need to be avoided. High dynamics, accelerations and velocities are yet another requirement that occur during the rest of the downstroke and when moving into the loading position and to the start of the glass forming phase.

To design a servo controller that satisfies these varieties of challenging demands, a very good understanding of the overall system including the glass pressing process is indispensable. In contrast to purely error-driven PID controllers, the approach in the present case is to base the controller design on physical models describing the servo electric mechanism and the forming process. Model based controllers have the advantage that they can "look ahead" in time and cause a system to behave in a desired manner at the outset, not having to wait until driving errors enforce that certain behaviour.

### *Servo drive requirements*

The drive requirements are mainly given by the plunger forces occurring in NNPB, and in PB processes. High accelerations and velocities are required in the first, high static forces in the latter. Therefore, since retro-compatibility is a given demand, one of the major challenges concerning the electric drive are the tight space constraints in combination with the high dynamic and static force requirements. Only highly optimised, custom designed drives represent a valid approach. Furthermore, the harsh mechanical and thermal environment calls for a very robust and reliable design solution for the mechanism. In that respect special care is necessary when selecting each individual component, such as the position feedback device. This particular element does not only need to be very robust, but its signal is required to have a high resolution as well. This is important since the model based controllers need to derive the acceleration from that position signal. The numerical operation to perform that task is very sensitive to signal noise, and therefore a low signal resolution would yield poor results.

## Description of the experimental unit

The realised experimental unit is designed to fit into Emhart Glass triple gob IS machines with centre distances of 4¼", and it has a stroke of 185 mm (7¼"). A custom designed brushless DC motor, integrated in each cavity, drives the outside nut of a hollow roller screw. The axially stationary nut forces the roller screw to move up and down and thereby actuates the plunger movement. The rotational degree of freedom of the screw is locked by two bronze keys sliding in keyways. Through a special adapter the roller screw is connected to conventional positioners or cartridges. Figure 1 shows a schematic view of one unit.

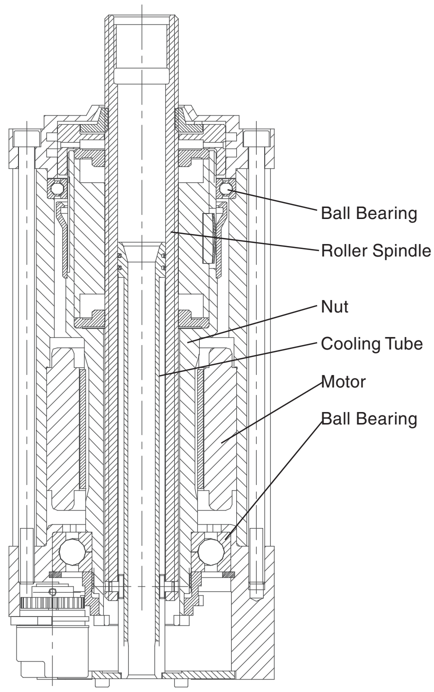


**Figure 1.** *Drawing of mechanism*

The control system is implemented on a PC-based controller and programmed in MATLAB® / Simulink. The real-time code is generated and compiled on a *host PC* and then loaded onto a *target PC* whose processor executes the control algorithm independently. This target PC is equipped with digital and analog IO boards for reading the encoder data and writing the motor commands to the amplifier. For experimental purposes signal monitoring and on-line adjustments of the control parameters can be done from the host PC. The user interface at the machine consists of adjustment buttons for setting the load position and the press force as well as a display visualising the pressing action for each cavity.

## Virtual system model

As already outlined, a thorough understanding of the electromechanical system and of the process are the key to designing the experimental unit and the servo controller.[2] For that purpose a physical model has been developed that allows to simulate and test and iteratively improve the complete system in virtual reality even before building any hardware. The model is divided into three parts which are presented in the next sections: the electromechanical system, the glass forming process and the controller. A simplified block diagram of the system is shown in Figure 2.

### *Electromechanical model*

The electromechanical model simulates the plunger mechanism and the electric motor with its amplifier. It includes masses and inertias, mechanical dampings and elasticities, friction, motor- and amplifier dynamics. Since the electromechanical model is crucial for the design of the model-based force controller, it is of prime importance.

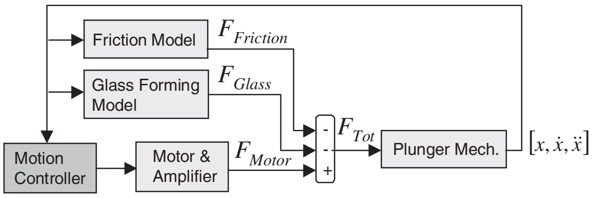


**Figure 2.** *Simplified block diagram of model*

*Linear and rotational friction* Besides the driving force of the motor and the glass forming force acting upon the plunger, an important factor that affects the dynamic behaviour of the mechanism is friction. On the one hand friction of the linear spindle motion, on the other hand rotational friction of the motor and the spindle-nut assembly need to be considered. The latter is mainly dependent on the normal force between the screw and the nut and their relative velocities. Figure 3 shows the relevant forces and torques.

Measurements for operation without glass showed that the overall friction contributions can be modelled by a velocity independent term and a linear and a quadratic term in speed. The quadratic term is caused by the ball bearings of the rotor and by the spindle-nut assembly, the constant and linear term are presumably associated to the linear motion. Based on these measurements the parameters of the friction models can be determined.

*Drive system* The motor is a torque-controlled brushless DC motor driven by a switched amplifier. As usual it is modelled by its linear torque equation $T=k_T \cdot i$ and the differential equation expressing the relation between the voltage $U$ and the current $i$

$$U = R \cdot i + L \cdot \frac{d}{dt} i + k_\omega \cdot \omega \tag{1}$$

The amplifier can be modelled as a PI-controller where the input error denotes the difference between the desired motor current (or -torque) and the instantaneously measured current.

### Model of glass forming force

The main parameters affecting the glass forming force are the parison and plunger geometry, the plunger velocity, the glass temperature and viscosity, and therefore, the heat transfer between glass and mould equipment. In the past a lot of effort has been put into the development of simulation models and programs describing the forming process.[3] Since the scope of these

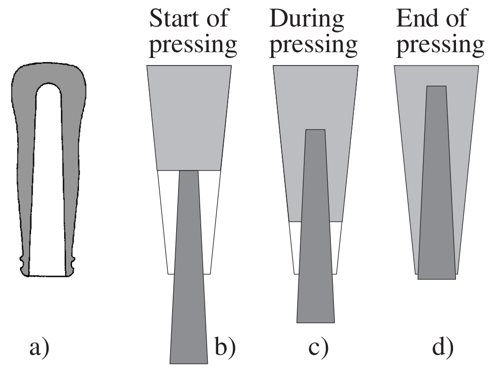


**Figure 4.** *Shape of typical parison a) and model of parison at different press phases b)–d)*

models is to study the impact of variations of the above listed parameters on the temperature distribution in the glass and on the glass distribution as detailed as possible, they are usually very complex and of high order. This results in an excessive computational effort and is not practical for the simulation of the dynamic plunger behaviour and an efficient controller design. Therefore, an axis-symmetric model of the plunger and the parison as shown in Figure 4 is used in which the inner and outer parison contours are described by the simplified geometry of frustrum cones.[4]

*Glass–hydraulic model* Beside the geometry certain assumptions are necessary to describe the flow of glass during the forming process. Based on observations and field measurements it can be assumed that in a first phase the glass is simply lifted towards the baffle end without any significant forces other than gravity acting upon the plunger. Only after the glass has filled out the baffle end as shown in Figure 4, the second phase, in which the plunger actually forms the glass, starts. In the present model this forming process can be interpreted as glass being pressed through a ring of varying length and of continuously varying inner and outer diameter. Considering an infinitesimally small ring element as illustrated in Figure 5 and neglecting inertial forces, the force equilibrium can be formulated taking into account pressure and shear forces

$$\frac{\mathrm{d}p}{\mathrm{d}x} + \frac{1}{r} \cdot \frac{\mathrm{d}(\tau \cdot r)}{\mathrm{d}r} = 0 \tag{2}$$

Under the assumption that glass behaves like a Newtonian fluid and that the relative glass velocity at

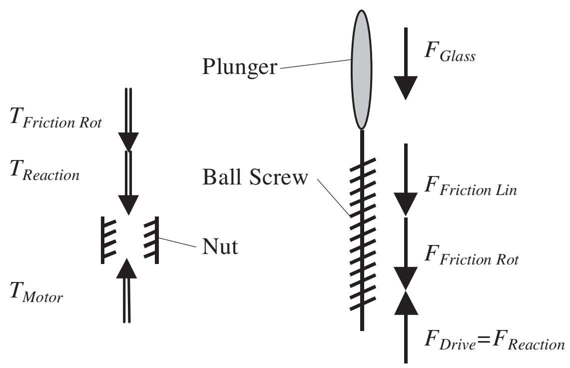


**Figure 3.** *Driving and friction forces*

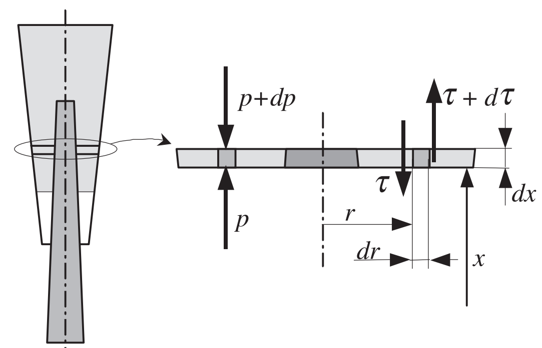


**Figure 5.** *Equilibrium of pressure and shear forces*

the contact surfaces (i.e. the plunger surface and the inner mould surface) is zero, the velocity field $v(x,r)$ can be calculated as a function of the pressure, the viscosity and the assumed geometry. This velocity field can then be used to determine the volumetric glass flow through the hydraulic restriction which is equal to the volumetric displacement of the plunger when pressing the glass. Integration of the resulting equation in $x$ yields the total glass force

$$F_{\text{glass}} = \eta(T) \cdot k_{\text{glass}}(x) \cdot \dot{x} \tag{3}$$

where $k_{\text{glass}}$ is a function of the plunger position containing merely geometry data, $\eta(T)$ the temperature dependant viscosity and $\dot{x}$ the plunger velocity. In order to reduce the computational effort, $k_{\text{glass}}$ can be calculated prior to the actual simulation and then be stored in a lookup table.

Glass viscosity Since the glass cools off during the forming process, the viscosity in Equation (3) is not constant but will increase over time.[5] Assuming identical heat transfer coefficients and identical temperatures for the plunger, and the blank moulds, the parison temperature is described by the following differential equation

$$\frac{\mathrm{d}}{\mathrm{d}t}T = -\frac{\alpha \cdot A}{m_{glass} \cdot c} \cdot (T - T_{m/pl}) \tag{4}$$

Thereby $\alpha$ is the heat transfer coefficient, $A$ is the total glass contact surface, including blank mould and plunger and $c$ is the specific heat capacity of glass. Note that $A$ is a direct function of the plunger position and that $\alpha$ decreases with the contact time as shown in Refs 6,7. The specific heat capacity $c$ can be determined for a given glass composition according to Ref. 8 using the empiric method of Sharp&Ginther. Finally the temperature dependent viscosity can be calculated applying the *Vogel–Fulcher–Tamman equation*[8]

$$\eta(T) = \eta_0 \cdot e^{\left(\frac{b}{T-T_0}\right)} \tag{5}$$

## Controller

Heart of the control system is the PC-based controller. The real time control program generates a current demand for the individual motors to control the plunger motion in every state of the system. The controller can be in three individual modes: position, velocity or force control, that can individually be activated and coordinated by an intelligent selection algorithm. The structure is shown in Figure 6.

The main controller is a PID position controller with position and force feedback. Additionally, a PI velocity controller acts as a limiting controller to ensure that the velocity demand, which can either be a stepped or a continuously time variable demand is not exceeded. Likewise the force controller ensures that the given force demand, which can either be stepped or profiled, is not exceeded during glass forming. This includes a model based approach in order to compute the actual glass force from the current signal and the computed acceleration signal in order to eliminate the need for an additional glass force sensor. The output of the three

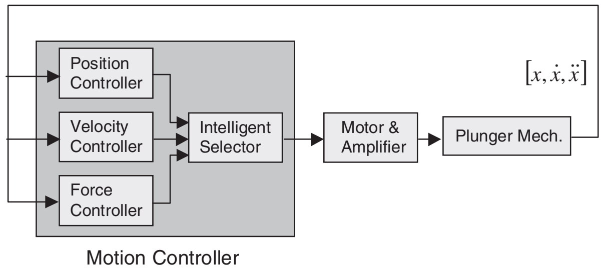


**Figure 6.** *Block diagram of model with motion controller*

controllers is fed into an intelligent selector block for model based coordination.

As a result the controller acts as a pure position controller at the start of the motion with a maximum possible acceleration. Only after the programmed velocity is almost reached does the velocity controller take over. Likewise the force controller takes over the regime during the critical glass forming process.

On top of the above described control strategy a force demand controller compensating for long term changes in glass viscosity, gob weight, wear or friction of the mechanism is active.

### *Model verification*

The verification of the model has been carried out both with and without glass. Measurements without glass allow to verify and eventually adjust and tune the parameters describing the electromechanical part of the system. Once that part describes the real physical system behaviour with the desired precision, tests in a real production environment under glass are used to verify the overall model including the glass forming force.

Verification of simulation without glass A comparison between the measured and the calculated plunger displacement, velocity and acceleration over a cycle for operation without glass is displayed in Figure 7 (solid lines represent simulation results, dashed lines with the crosses represents the measurements). The plunger moves from the down position to the servo controlled loading position, then at maximum speed to the point

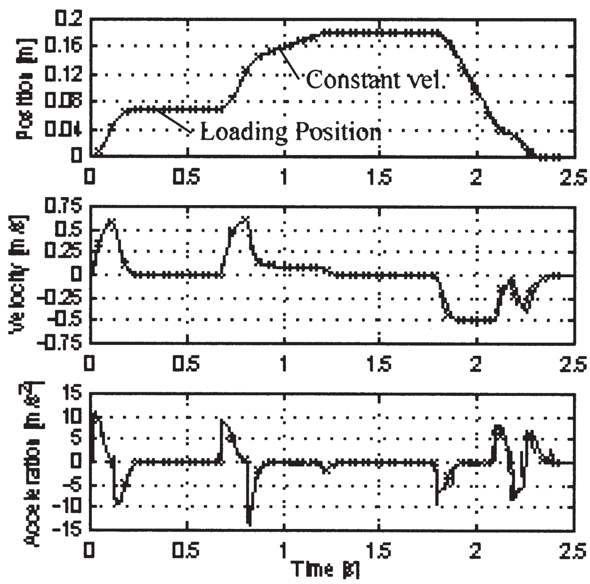


**Figure 7.** *Measured (dashed line with crosses) and simulated (solid line) position, velocity and acceleration of plunger without glass*

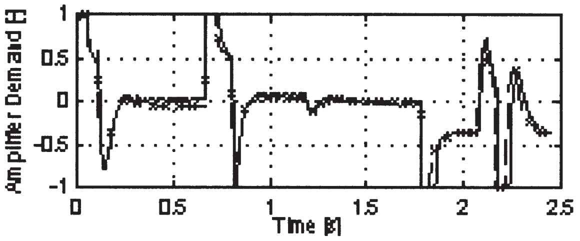


**Figure 8.** *Measured (dashed line with crosses) and simulated (solid line) controller output for trial without glass*

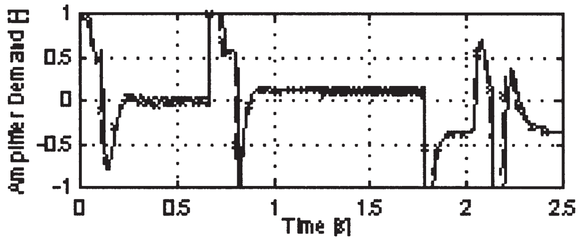


**Figure 10.** *Measured (dashed line with crosses) and simulated (solid line) controller output for trial with glass*

where the pressing starts, from there it decelerates towards a lower pressing speed and finally it is retracted and moved back to the starting point. The agreement between measurement and calculation is excellent.

As Figure 8 illustrates, this is not only true for the kinematic data, but also for the measured and calculated current demand, the signal sent to the amplifier by the controller.

Verification of simulation with glass The same type of measurements are carried out for operation under glass. Figure 9 shows the simulated and the measured kinematic data. Clearly, the major difference to the laboratory trials without glass is the pressing phase. Now the plunger does not move up at a constant velocity as before, but the motion is continuously adapted in a way that the pressing force remains constant. The fact that the simulations and the measurements match extremely well proves the surprisingly high accuracy of the applied glass force model.

The concept of actively controlling the pressing force and keeping it constant is also expressed in Figure 10 showing the motor current demand. Both the simulated and the measured signal during the pressing phase are kept around a constant level.

## Experimental results

### *General experience*

After extensive laboratory testing, field tests have been carried out at Wiegand Glas, Germany, where the experimental unit was successfully operating on an AIS TG 4¼ in a real production environment during a total of six months. Various typical articles such as 0·25 l and 0·5 l Dosenflasche, 0·5 l Obus Poly and Standard III and IV bottles have been produced in both NNPB and BB-processes. The general experience and the first results are very encouraging.

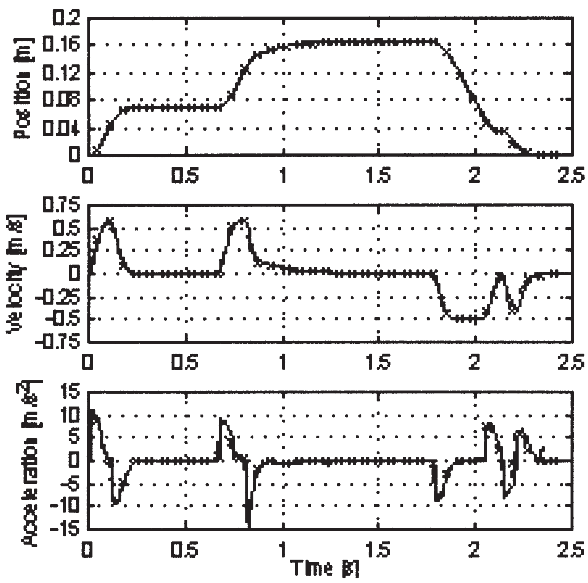


**Figure 9.** *Measured (dashed line with crosses) and simulated (solid line) position, velocity and acceleration of plunger with glass*

Glass forming It could be shown that the possibility of actively controlling the motion and the pressing force of the plunger reveals some major benefits for the parison forming process, especially in NNPB production. Generally speaking, the repeatability of the process is improved considerably, and hardly any adjustments or other operator interventions are necessary during operation. Changes in glass viscosity, gob weight, wear or friction of the mechanism can be compensated for by the automatically adjusted press force. As a result, major critical defects, unfilled finishes and overpressing have been prevented.

Electromechanic performance The field tests proved that an extremely compact electromechanical drive, satisfying the severe space constraints given by a 4¼" plunger mechanism can be realised. The achievable dynamic and static performance was amply sufficient for NNPB processes, and during the extensive period of field testing it could be shown that the electromechanical design meets the criteria to satisfy a reliable functioning under harsh conditions.

Additionally based on the virtual model experience gained through the field tests simulations proved that the plunger is also able to handle PB jobs even though they require considerably higher pressing forces than a typical NNPB job.

### *Comparison SEPL versus pneumatic plunger*

Based on the same glass forming model described above and the Emhart Glass experience in simulating the dynamic behaviour of pneumatic mechanisms(4) comparisons have been made between the performance of the servo-electric plunger and a standard pneumatic plunger. This comparison was based on the field trials with the experimental unit which was installed on one section of an AIS TG 4¼ with all other sections being equipped with pneumatic plungers. A result of such a comparison is shown in Figure 11. It shows that the servo-electric plunger is not only faster in moving to the load position but also faster in reaching the critical press position where the actual glass forming process begins. Even though the following pressing process is much smoother for the servo-electric plunger, it reaches the filled position much earlier than the pneumatic plunger. This gain in time can be used either for

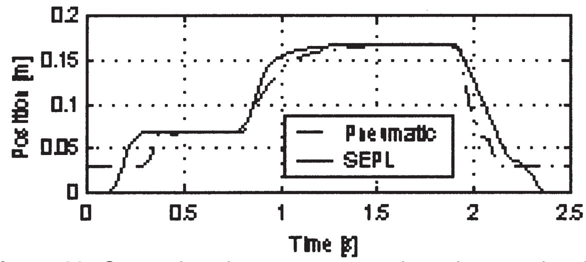


**Figure 11.** *Comparison between pneumatic and servo-electric plunger mechanism*

higher speed on the blank side or for increased quality in terms of a more stable parison due to increased plunger contact time.

## Conclusion

The extensive research work conducted during the development of an experimental servo-electric plunger mechanism including its controls led to a profound understanding of the requirements of such a mechanism. The work showed that only the application of modern control strategies with model-based control algorithms generates the application and user benefits needed to justify the higher cost. The paramount application benefit proved to be the stability of the parison pressing process that does no longer need to be continuously supervised by the machine operator. Operator interventions are reduced to a minimum and can be based on information providing full transparency of the actual pressing process. The proactive avoidance of critical defects without relying on highly skilled and attentive machine operators can justify the demand of applying a sophisticated technology. The future availability of a servo-electric plunger mechanism on the NIS machine will be another significant step towards automation of forming machines in the glass container industry.

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