# Automation of the car battery lid assembly operation

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### Abstract

Automation of an assembly operation in an automotive lead/acid battery production plant is described in the paper. The operation—assembly of the polypropylene lids on the battery containers—is automated using robot technology. During the process of lid assembly, it is necessary for two plate stack electrodes to slide into two hollow lead terminals in the lid. In the part mating task the sticking is possible to occur bringing the assembly process into the halt. To design an automatic assembly system the lid assembly operation is considered as a problem of multiple peg-in-hole insertions. The paper investigates the basic principles of a multiple part mating task with special regard to the lid assembly. The theoretical and experimental findings are presented enabling improved understanding of the lid assembly process. On this basis, the robot workcell is built and assembly strategy proposed. Presented are the design of the workcell peripheral devices and incorporation of the workcell into the existing automotive battery production line.
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## 1. Introduction

Electrical batteries play an important role in the automotive industry. Wet lead/acid batteries have proven over decades as very reliable, attaining in the same time the highest cost-performance ratio. While the worldwide battery market trends forecast a quantitative growth [1], the manufacturing process of the lead/acid batteries presents potential danger for the worker's health because of the poisonous lead oxide presence in the air. To reach higher production objectives along with workers protection, the increase of the degree of automation in the battery manufacturing process is crucial [2–4]. Nowadays, the most advanced automatic systems in the battery production can be found in the plate manufacturing, plate stacking, and quality inspection [5–9].

In the battery production plant studied in this paper, a wide range of battery types with varying performance characteristics are manufactured. The lead metal required for battery production is primarily acquired from recycling scrapped batteries [10]. At present, five different automotive battery types can be assembled on the considered assembly line. Each battery type requires its own settings and adaptations of tools and feeders along the line. Due to fast responses to market demands, the assembled battery types are changed several times even during a single working shift. Battery types differ in physical dimensions of the containers and different forms of the battery lids. The width of the battery container is the same for all types (175 mm), while the length varies for each type (160, 207, 242, 278, and 353 mm). Additionally, each type has two variations of the container height, 175 and 190 mm

The assembly line where the batteries are manufactured encompasses several working operations organized along a linear conveyor belt. First, the negative and positive battery plates are manufactured by pressing the lead oxide paste onto the plate grid frame. After drying, the plates are assembled into the plate stacks. One plate stack is composed from several positive and negative plates separated by separators and welded together, thus forming a single battery cell. Battery cells are then inserted into polypropylene battery containers, each laid into a separated chamber, and electrically interconnected. Thereafter, the battery lid is set over the container and sealed by a thermal procedure. The lid position is automatically verified prior to the sealing operation, while after the operation the assembled battery is checked for the perfect sealing. Finally, the

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assembled battery proceeds toward the filling with the acid electrolyte, electrical formation and testing stages. While the operations of plate forming, plate assembly and cell insertion into the container are already automatized, the operation of the lid assembly on the battery container is manual.

Prior to the lid assembly on the battery container, the battery is half assembled. The plate stacks are inserted into six container chambers and electrically interconnected by welding, thus forming a compact entity. On the top of the outermost plate stacks, two lead electrodes are mounted extruding up for about 30 mm above the edge of the container. The extruding electrodes—two cylindrical lead pegs—are cone-shaped at their ends.

The battery lids are made from polypropylene material containing six openings intended for electrolyte filling. Additionally two hollow lead cylinders are mounted into the plastic lid construction, aimed as the outer part of the battery terminals. On the lower side of the lid terminal openings, there is a chamfer aimed for easier lid assembly. In Fig. 1 the half assembled battery together with the battery lid is presented in the stage prior to the lid assembly operation.

During the process of the lid assembly, it is necessary for the plate stack electrodes to slide into the hollow lead terminals in the lid. The electrodes and the chamfer openings are the outer most parts of the container and the lid and thus make the initial contact. In the manual lid assembly, the lid is manipulated by the worker, while the battery container is fixed at the conveyor belt. The worker holds the lid by a hand and compliantly manipulates it while being in contact with the electrodes. After achieving the initial insertion of both electrodes at the chamfer orifices, the lid is pressed down and set to the container's upper edge. The lid assembly task often fails due to an insertion sticking on one of the lid sides. In this irregular cases, a corrective action is needed to bring the

assembly to a successful finish. In the manual assembly the worker applies either a strong push or hit at the stuck lid side. Sometimes, the only action enabling proceeding is removing the lid, bending the electrode to proper position, and repeating the assembly operation. The occurrence of the assembly halts depends on the battery type and the quality of working operations accomplished prior to the lid assembly. The failure rate of the first assembly attempt can momentarily vary from 0% up to 100%, but is usually under 30% in normal production conditions. It was estimated that among failed attempts it is less than 1% of cases where the manual electrode bending is needed to successfully finish the lid assembly. However, after the worker's intervention, a 100% successful lid assembly rate is normally achieved.

The automatic system aimed for automatic lid assembly needs to provide the lid storage, lid feeding, lid manipulation, and lid assembly functions. The basic requirements for the system are to meet the production line cadence of 100 products per hour, to provide a lid storage for at least half hour production, and to provide flexibility for all battery types in production. When designing the automatic system, the problem of the lid sticking needs to be properly addressed. For successful automation of operation, the system should be able to detect, adequately distinguish and react to the lid assembly faults.

In this paper a robot cell performing automatic lid assembly on the battery container is presented. Firstly, the problem of the battery lid assembly operation, treated—from a robotic assembly point of view—as a peg-in-hole insertion problem, is investigated with theoretical background and practical laboratory evaluation. Secondly, the robot cell setup is presented incorporating for this task specially designed robot gripper and peripheral feeding devices.

## 2. Theoretical background

When a round peg (in our case a lead electrode) is being inserted into a round hole (in our case a hollow lead terminal), the peg may be in contact with the hole owing to positional inaccuracy. The positional inaccuracy may be caused by many sources, such as positional inaccuracy of the manipulator, tool wearing, and most common, variation of part tolerances and position error of both parts after being fed. During mating two objects with positional inaccuracy, undesired and possibly harmful reaction forces can appear. In such a moment, the motion of the peg is constrained by the geometry of the hole, and some compliance in the system is needed to successfully accomplish the mating task.

In the literature, assembly processes are normally considered as quasi-static problems because the effect of friction dominates inertial effects. The force/moment analysis of the round peg-insertion problem was firstly
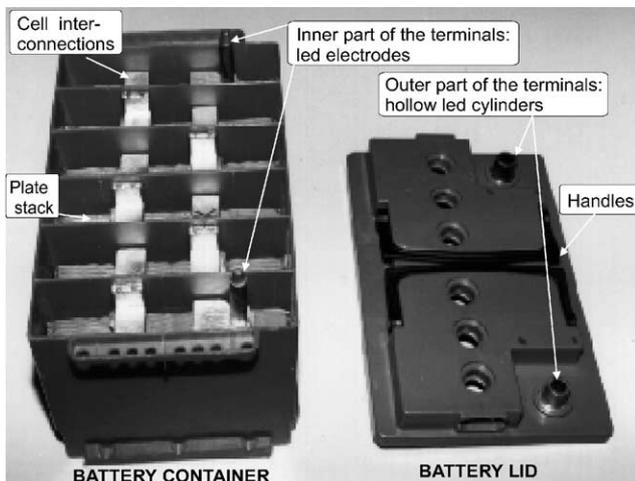


Fig. 1. Half assembled battery and the battery lid prior to the lid assembly operation.

presented in [11]. Later, the wedging and jamming conditions were identified, and the ways to avoid these modes of insertion failure were recommended in [12]. These studies eventually led to the development of a remote-center-compliance (RCC) device [13] which is a compliant mechanism nowadays widely used in industry to passively compensate position and orientation uncertainties during an assembly process. Other efforts have been made to provide an in-depth understanding of a single round peg-in-hole assembly [14,15] and to find a general insertion strategy [16].

In the lid assembly task two lead electrodes are being inserted into two lead terminals simultaneously. Accordingly, the operation needs to be considered as the problem of the double cylindrical peg-in-hole insertion task. The difference with respect to the single peg-in-hole insertion is that multiple insertion is a three dimensional problem and thus, the initial positional errors prior to the insertion could appear as lateral and angular errors in space. The problem was extensively studied in [17], where a geometric and quasi-static conditions were described for a two dimensional dual-peg insertions. In the study, the possible contact states were identified and jamming diagrams defined. The limits of non-parallelism for rigidly connected pegs when avoiding the instance of wedging were derived. As an alternative to the passive compliance based assembly strategies, the different strategies were also proposed incorporating the active compliance control. The active compliance is a controlled robot motion as a response to the measured reaction forces. A kind of active approach to the

multiple peg insertion was examined in [18]. The authors introduced the perturbation to the robot end-effector and developed the algorithm reacting to the measured contact forces. On the other hand, in [19] was shown that the successful multiple part mating can also be achieved by utilizing a simple differential touch sensor and a behavior-based insertion algorithm.

The specific situation when assembling the battery lid on the battery container is illustrated in Fig. 2. The left side of the figure is a three dimensional presentation of the lid assembly task. The coordinate system is defined in the place where the lid is grasped by the robot gripper and external setting force applied. For the majority of the lid types the grasp with regards to both terminals is asymmetrical because of the centrally mounted battery handles. The distances to the grasp center are denoted as $d_1$ and $d_2$, and the angular displacement due to grasping or manipulation errors as $\theta_{z0}$. The detailed figure on the right presents the conditions when the terminal is approaching electrode with initial lateral and angular displacements ($\varepsilon_0$ and $\theta_0$) defined between the electrode and terminal axes. In the task a peg with radius $r_2$ is being inserted into a hole with radius $R$. The chamfer inclination is denoted as $\alpha$ and the chamfer width as $w$. Each electrode is not fixed in the battery container and can to some extent compliantly move along with the plate stack that moves around the point of its lower edge. The distance measured along the peg axis to this point of compliance is denoted as $L_g$, while the lateral displacement of the point from the hole axis is denoted as $U_0$.
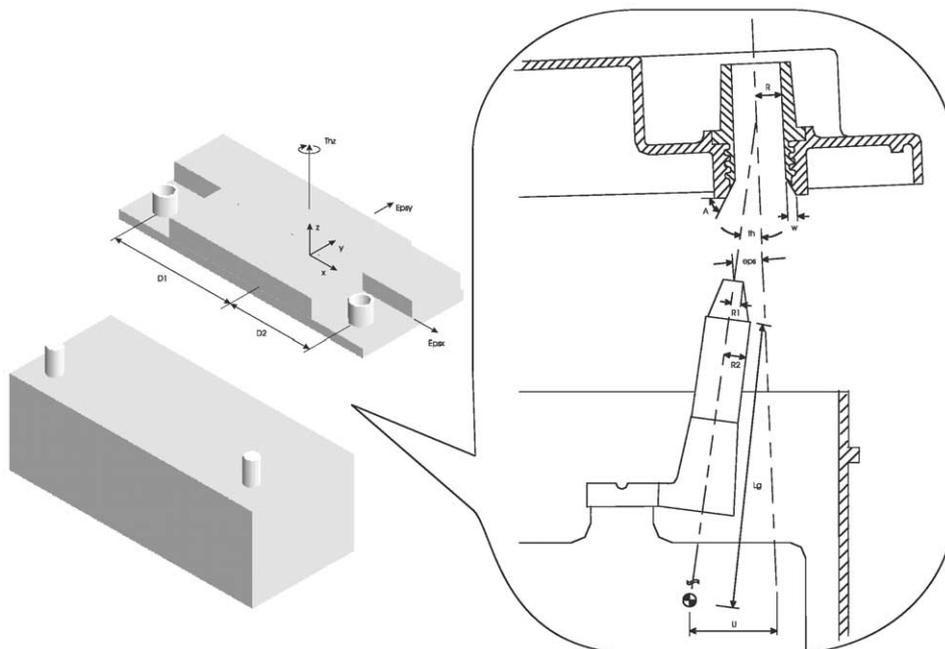


Fig. 2. Battery lid assembly operation—multiple peg into hole insertion problem.

From the mating task geometry the first condition allowing the successful lid assembly can be derived.

**Condition 1.** The lid assembly operation can only be successfully accomplished when in the moment of initial contact the upper outer edge of the electrode falls inside the region defined by the lower outer edge of the hole chamfer. The condition for each electrode–lid terminal pair is thus expressed as:

$$|\varepsilon_i + L_g \sin \theta_0| < R - r_1 + w, \tag{1}$$

where index $i$ denotes the left or the right electrode–terminal pair ($i = 1$ or $2$). Positional error $\varepsilon_i$ is a function of the grasp lateral and angular displacements and is expressed as:

$$\varepsilon_i = \sqrt{\varepsilon_x^2 + (\varepsilon_y + d_i \theta_{z0})^2}. \tag{2}$$

During the part mating task, when parts are contacting each other, the contact forces occur. These forces, when in disproportion, can cause the mating process to jam or stick. In [12], two such situations are differed, named jamming and wedging of the peg in the hole. Fig. 3 illustrates the wedging and two different jamming situations.

The state of the jamming occurs when the forces and moments applied to the peg are in the inappropriate proportions. In the case of cylindrical peg insertion into a cylindrical hole only one or two point contact between the mating parts is possible. When in the one point contact, the contact force vector is composed of the force normal to the hole surface ($f_1$) and the friction force $f_{fr}$ (see Fig. 3a). The relation between the components is $f_{fr} = \mu \cdot f_1$, where $\mu$ denotes the static friction coefficient of the lead to lead contact. The lid terminal is set onto the electrode with the setting force $F$. The reactions to this force are forces in the electrode longitudinal and transverse directions ($F_z$ and $F_x$). The event of one point jamming occurs when the resultant contact force, after applying setting force, stays inside

the friction cone whose shape is determined by the friction coefficient $\mu$. The condition $F_z > \mu \cdot f_1$, with assumption $F_x = f_1$ can thus be expressed as a condition for avoiding jamming while in the one point contact:

**Condition 2a.**

$$\left| \frac{F_{xi}}{F_{zi}} \right| < \frac{1}{\mu}. \tag{3}$$

When the two point contact between the peg and the hole is established, an additional moment acts to rotate the peg. The two point jamming situation occurs in the instant when the peg rotation counteracts the direction of insertion. This situation is depicted in Fig. 3b. The jamming situation is avoided if the inequality describing the balance of moments is met:

$$M_i - f_{1i} l_i + \mu r_2 (f_{2i} - f_{1i}) < 0, \tag{4}$$

where

$$f_{1i} = (F_{zi} - \mu F_{xi})/2\mu, \tag{5}$$

$$f_{2i} = (F_{zi} + \mu F_{xi})/2\mu. \tag{6}$$

From the above Eqs. (4)–(6) the general condition for avoiding the two point jamming situation is derived:

**Condition 2b.**

$$\left| \frac{M_i}{r_2 F_{zi}} + \mu(1 + \lambda)\frac{F_{xi}}{F_{zi}} \right| < \lambda, \tag{7}$$

where $\lambda$ is expressed as:

$$\lambda = \frac{l}{2\mu r_2}. \tag{8}$$

The factor $l$ denotes the depth of insertion.

The situation of wedging can occur after two point jamming has occured. In contrast to the imbalance of forces and moments during jamming, the wedging is the consequence of the instant geometrical relations. When the process of insertion is stopped due to the two point jamming the setting force $F$ is reduced to zero, however
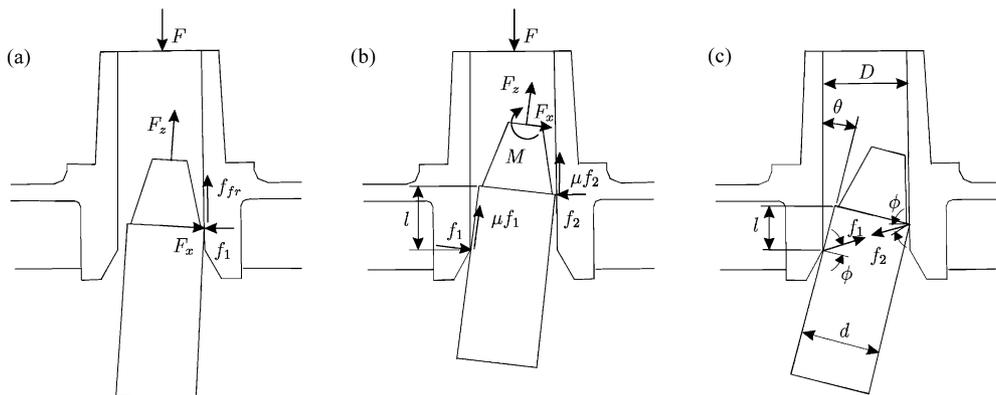


Fig. 3. Three irregular peg-in-hole insertion situations: (a) one point jamming, (b) two point jamming, and (c) wedging.

the vectors of reaction forces $f_1$ and $f_2$ are due to the hole plastic deformation still present and are located inside the friction cone and pointing towards each other. The geometry of the wedging situation established at the limit value of insertion depth $l$ is presented in Fig. 3c. If the two point contact occurs at deeper insertion the wedging is not possible to occur.

From the geometry on Fig. 3c two equalities can be written:

$$\tan \phi = \mu = \frac{l}{d}, \tag{9}$$

and

$$l\theta + d = D, \tag{10}$$

from which the condition for avoiding the wedging is derived:

**Condition 3.** To avoid wedging situation when the peg is stuck into the hole, two-point contact between peg and hole must occur at a value $\theta = \theta_2$ obeying

$$|\theta_{2i}| < \frac{D - d}{\mu d}. \tag{11}$$

To achieve successful lid assembly all conditions should be met on both electrode–terminal pairs. Since both electrodes are not rigidly connected and are independently compliantly moving in certain extent, the conditions for avoiding jamming and wedging can be generalized to each pair separately. This is in equations indicated by the index $i$ denoting the left or the right electrode–terminal pair ($i = 1$ or $i = 2$).

## 3. Experimental evaluation of the lid assembly operation

In order to evaluate the setting conditions for the battery lid assembly operation and to properly plan feeding and setting accuracy of the assembly robot cell the experimental setup was constructed in a laboratory environment. The setup encompassed the manipulation and measurement systems aimed for performing the lid assembly operation while assessing the motion kinematics and contact forces of mating parts.

### 3.1. Manipulation and grasping of the lid in experimental environment

The manipulation of lids during experimental assembly was performed by the industrial robot Motoman SK6. The robot has anthropomorphic configuration with 6 rotational DOF. Its maximal allowed payload is 6 kg when attaining the $\pm 0.1$ mm positioning accuracy.

For automatic lid grasping a special robot gripper was designed. The gripper is based on one vacuum suction cup which holds the lid during manipulation. Various gripper designs including more suction cups were tested

to obtain more stable grasp. However, in order to accommodate the gripper for the five lid types momentarily in production, the construction with single suction cup and four rubber stoppers placed around the cup proved to provide appropriate grasp stability and adequacy for various lid types. However, this gripper design deteriorates lid assembly performance due to necessary asymmetrical lid grasping and compliant nature of one point pneumatic grasp. The Festo VAD-1/8 vacuum generator was used providing the suction cup grasping force of 120 N. Minor electrode jamming on a single lid side can cause the lid to rotate around the outer edge of the rubber stoppers or bending of the lid. This aggravates the fulfillment of the insertion conditions and causes the lid to become stuck, usually on the distal lid side. The design of the vacuum gripper with one suction cup and four rubber stoppers is illustrated in Fig. 4.

### 3.2. Measurement setup

The measurement setup used in the analysis consisted of two systems; the first for determining the contact forces between the mating parts and the second for measuring the parts motion trajectories.

The assessment of contact forces was accomplished by the JR[3] 40E15A-15 163 six axis force sensor (JR[3], Inc., Woodland, USA). The sensor was mounted in the robot wrist between the last robot link and the gripper. Its amplified output signals spanned in the range of $\pm 10$ V were acquired by the Burr-Brown data acquisition board with 12 bit resolution (Burr-Brown Corporation, Tucson, USA). Prior to the experiment the force sensor has been calibrated with precision weights to 1 N force accuracy and 0.1 Nm torque accuracy.

The motion kinematics of mating parts was assessed by the OPTOTRAK contactless position measuring system (Northern Digital Inc., Waterloo, Canada). The
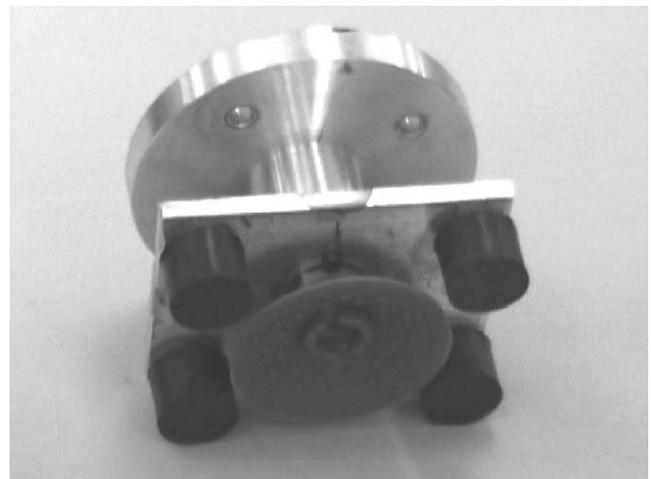


Fig. 4. Vacuum gripper designed for multi-type battery lid grasping.
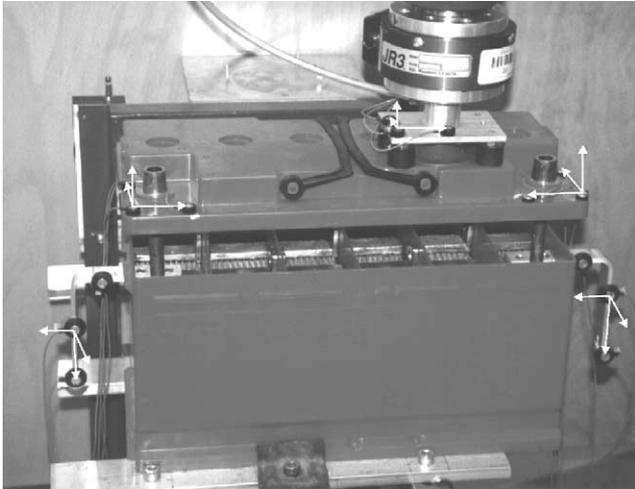
Fig. 5. Lid assembly kinematics and force measurement setup.

system measures the 3D positions of active markers (infrared LEDs) with 0.1 mm accuracy. Markers, about 1 cm in diameter, were attached to the measured objects with double-sided tape. The distances between markers were approximately 4 cm. In Fig. 5 the lid grasp, force sensor and arrangement of the markers are shown for the lid assembly operation of the L5 battery type. The L5 battery type is the type with the largest dimensions and centrally mounted handles and is thus considered as the most difficult for assembly.

Five sets, each incorporating three markers, were used to define the position and orientation of two electrodes, two hollow terminal posts and the gripper. Markers were attached as close as possible to each object in a way that all three were defining a plane. For determining the position and orientation of the electrodes, which are during assembly covered by the lid and thus not visible to cameras, the additional rods were rigidly mounted on both outer plate stacks where the electrodes are attached. The rods were extruding out from the container through the side holes and the markers were attached to their outer parts. According to the markers position, to each object a relative coordinate system was attached as illustrated in Fig. 5. Each relative coordinate system was translated into the object center according to fixed and prior to measurements determined displacement. In this way, the action point of the setting force, the tip position of each electrode, and the central line position and orientation of electrodes and terminals were acquired. Prior to the experiment the system has been calibrated in order to eliminate those errors not originating from the measurement equipment inaccuracy. The lid has been placed on the battery in its exact mating position. Assuming that in this configuration the electrodes were positioned exactly vertically, relative transformations between local coordinate systems have been determined. In this way, the references for the zero lateral and angular error were defined. All further

measurements were then compared to this initial position, thus eliminating absolute measurement errors. Based on the analysis of position measuring system inaccuracy and placement of infrared markers, the positional measurement inaccuracy has been estimated to less than 0.1 mm and the angular inaccuracy has been estimated to less than 0.6°. From the positional data the space angular and lateral displacements were calculated, and the two point contact condition supervised. Namely, the geometrical condition defining whether the mating parts are in the two point contact stage was derived from the Eq. (10). It was assumed that the two point contact occurs when the product of the insertion depth $l$ and the rotational error $\theta$ is greater or equal to the term $2(R - r)$:

$$l\theta \geqslant D - d = 2(R - r_2). \tag{12}$$

Forces and moments assessed by the robot wrist force sensor ($F_s$ and $M_s$) were transformed from the sensor coordinate system into the forces and moments ($F_e$ and $M_e$) expressed in the coordinate system of the electrode according to the matrix equations

$$F_e = {}^sT_e F_s, \tag{13}$$

$$M_e = {}^sT_e M_s + {}^sr_e F_e, \tag{14}$$

where ${}^sT_e$ is a rotational matrix describing the rotation of the sensor coordinate system into the electrode coordinate system, and ${}^sr_e$ is a displacement vector between both system origins.

### 3.3. Experimental protocol

The battery was firmly attached to the supporting rack. The measurement process began with the calibration procedure of measurement equipment and reference coordinate frames as described in the previous section. After the calibration the lid was grasped by the robot and manipulated to accomplish the assembly operation. Throughout the assembly operations all significant lateral and angular displacements of the lid hollow lead terminals were assessed relative to the battery electrodes.

The parameters significant for successful lid assembly were defined on the basis of analytical analysis and experimentally evaluated in order to determine the primary cause for the assembly failure.

The empirical data acquired during the assembly operations have been off-line analyzed. Based on the visual inspection, the measurements have been classified according to the assessed cause of problems that aggravated the lid assembly operation. Each measured sequence pertaining to specific assembly operation has been analyzed separately. No averaging of measured data has been performed, since each problematic situation was far too specific from the point of view of the relevant assembly parameters. Based on the

measurement uncertainties introduced in the section describing the measurement setup and the corresponding equations describing single and double peg-in-hole insertion conditions, confidence intervals were estimated for each specific situation. The intervals were assessed from the differential sensitivity analysis that determines the jamming or contact condition deviation due to a relative measurement error in the collected data. The depicted confidence intervals were computed for the largest absolute measurement error that could possibly occur, due to the limited accuracy of the measurement equipment.

### 3.4. Experimental results

A set of testing lid assembly trials were accomplished for a range of different setting conditions encompassing various initial lateral and angular displacements. Quasi-static conditions were achieved by performing lid assembly under slow vertical motion speed, while the data were sampled at 10 Hz sampling rate.

In the following section the results for two different assembly tasks are presented. The first task with one electrode removed was aimed at proving that neither of jamming situations can occur in a single peg-in-hole insertion even in the worst case of displacement error during the battery assembly. On the other hand, the second assembly task analyzes the conditions that are the main cause for unsuccessful lid assembly during the regular operation. It was assessed that the so called chamfer jamming explained in the latter section is the only reason for unsuccessful lid assembly, not taking into account the 1% of cases where the manual electrode bending is needed to finalize the assembly.

Throughout the results section, where the contact and jamming conditions are investigated, alongside the computed conditions also the confidence intervals are presented which were determined from the known measurement uncertainties. Since Eqs. (3) and (7) describing the one and two point jamming conditions are undefined when interaction force is zero, both conditions were analyzed only when the contact between the mating parts was detected. The beginning of the contact is indicated with the vertical dashed lines.

Since the usage of a single force measurement system enabled assessment of the contact forces only on a single electrode–terminal pair, the assembly conditions were firstly evaluated performing the lid assembly task with one electrode removed. By mating the proximal electrode–terminal pair the influence of the lid compliance was reduced, while the influence of the gripper compliance was eliminated by the additional fixation mounting of the lid to the gripper. Fig. 6 presents the experimental evaluation results for the lid assembly task of the L5 battery type. Presented trial was accomplished

with the 7.5° initial angular error. Graphs 6a, b and c present the angular error, lateral error and insertion depth trajectories, respectively. Graph 6d is a graphical presentation of the geometrical condition for the two point contact (Eq. (12)). From the graph it can be seen that the inequality (12) held, i.e. the mating parts were in two point contact, during the time period from 14th to 21st second. Graphs 6e and f present verifications of one and two point jamming conditions. It was visually observed and also proved by the measurement results that neither of jamming situations occured. Inequality (3) characterizing one point jamming held throughout all the process (see Graph 6e), while the condition (7) characterizing the two point jamming was also fulfilled throughout the two point contact phase.

The above single electrode-in-terminal insertion example was accomplished with the highest initial angular error $\theta_0$ that is permitted by geometrical condition (1). It was demonstrated that none of the possible jamming and consequently wedging occurred. Therefore it can be concluded that the geometrical structure of the single electrode–terminal mating task, according to reasonable clearance between both parts, ensures successful assembly without jamming or wedging as long as condition (1) is met. On the other hand, in the real lid assembly task two simultaneous electrode–terminal insertions are performed, including the effects of the lid and gripper compliance. The example of the real lid assembly operation is presented in Fig. 7. The upper two graphs, 7a and b, present the forces and moments measured at the robot wrist when setting the L5 type lid. Graphs 7c and d present the angular and lateral displacements between mating part axes. Displacement trajectories are given separately for each electrode–terminal pair. Graph 7e is an illustration of the two point contact verification based on (12), while Graph 7f depicts the advancement of insertion presenting the insertion depth $l$ separately for each electrode.

From Fig. 7 it is evident that the contact between the lid and electrodes was established at 3.4 s when the contact forces emerged. The insertion depths of both electrodes were raising simultaneously until 6 s. At this moment the distal electrode on the left lid side stopped progressing, which resulted in lid rotation around the gripper compliant axis. The angular error of both electrodes increased disproportionally implying simultaneous lid bending. The proximal right electrode meanwhile proceeded toward the final position. At the time instant 10 s the stuck electrode was released and instantly inserted to the final position. Since the insertion depth of the distal electrode at the instant of jamming had negative value the electrode was obviously contacting the chamfer region. The phenomenon named "chamfer jamming" is explained in Fig. 8.

When sliding over the chamfer, one point jamming is more likely to occur because of the higher angle between
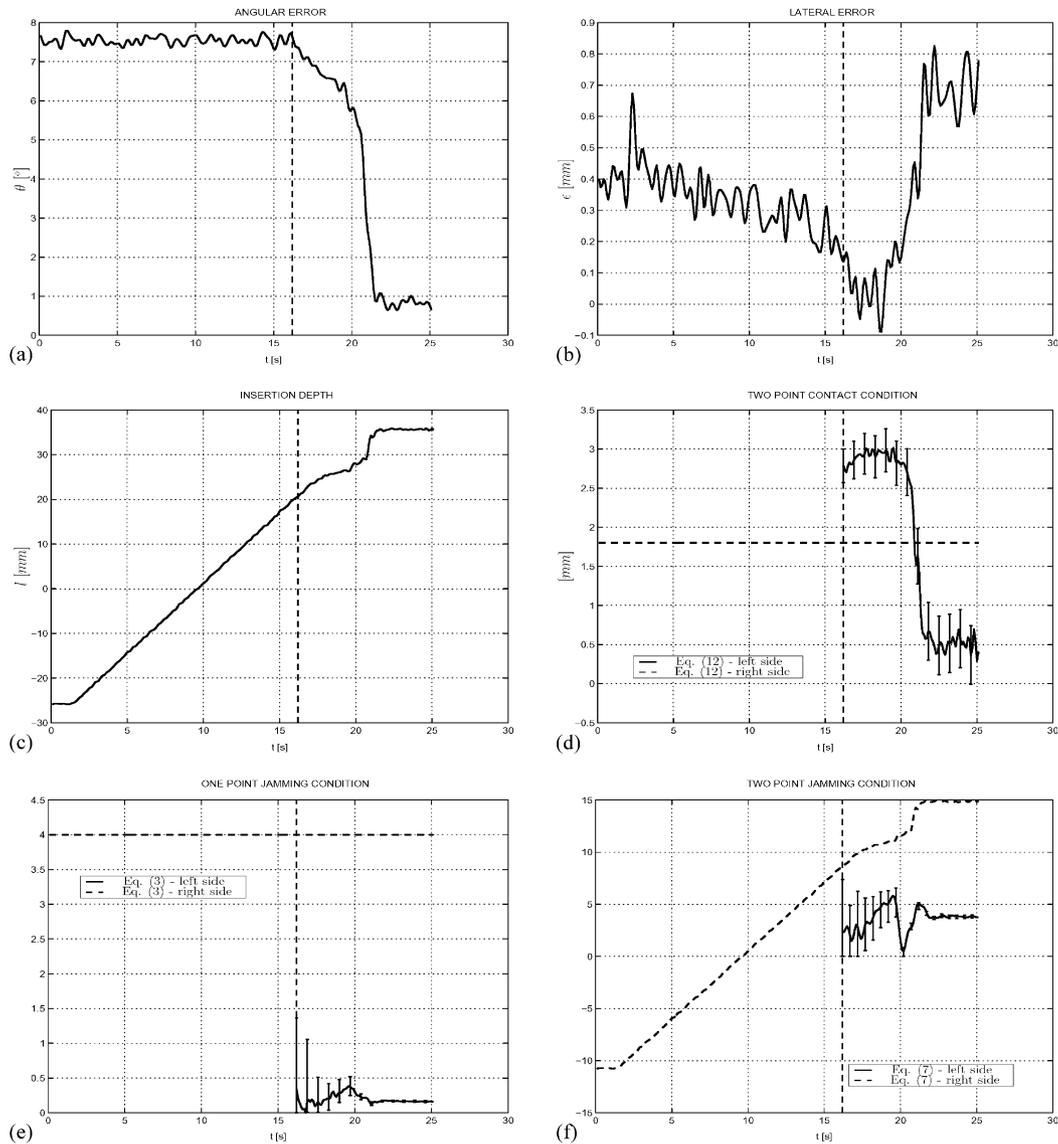
Fig. 6. Single electrode-terminal pair mating task.

the setting and friction forces $F_z$ and $f_{fr}$ (see Fig. 8a). The problem, most frequently demonstrated at the distal electrode of the L5 lid type, is that the one side chamfer jamming causes bending and rotation of the lid that deteriorates the sliding conditions. The successful lid assembly, following this irregular situation, can be achieved in two ways.

**Strategy 1.** After one side chamfer jamming the vertical motion is proceeded resulting in increase of the contact forces. Consequently, the lid will rotate and bend and bring the electrode into twopoint contact at the chamfer (Fig. 8b) and afterwards transfer the contact point to the chamfer edge (Fig. 8c). From this point, because of the friction cone inclination change, the instant slip and

insertion is feasible. The occurrence of this scenario was presented in Fig. 7. A drawback of the approach consists of the high contact forces, demanding a robust manipulation device. The intensive bending of the lid is likely to be detrimental to product quality.

**Strategy 2.** After one side chamfer jamming detection the vertical motion is stopped, the lid is released left lying unset on the battery container. When released, the lid unbends bringing the stuck electrode–terminal pair automatically into the position presented in Fig. 8c. Afterwards, the lid is pressed down and simultaneously laterally pushed by the gripper at a point closer to the distal electrode. The approach allows utilization of a small size manipulating device, but requires a sensory
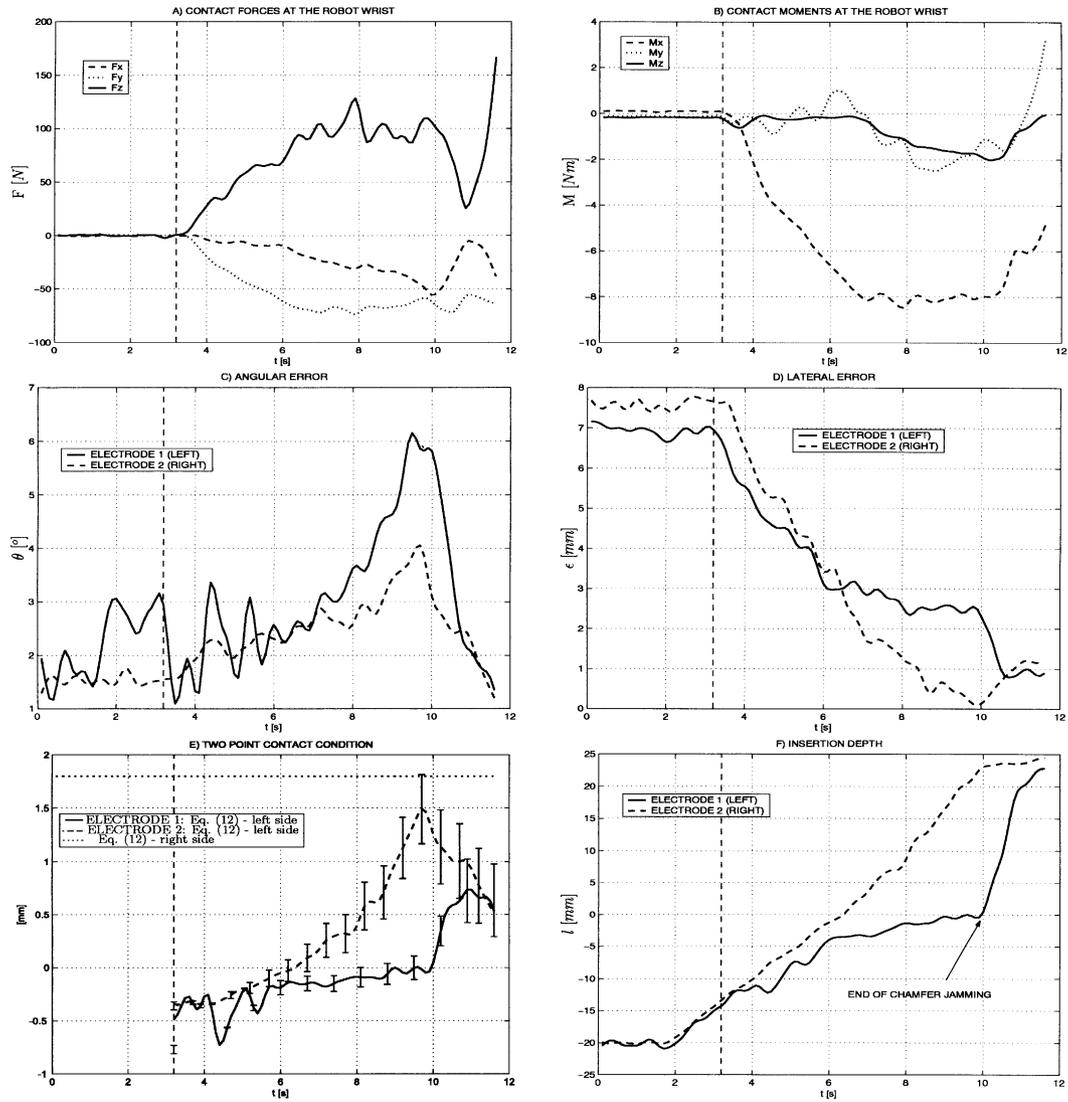
Fig. 7. Double electrode-terminal pair mating task.
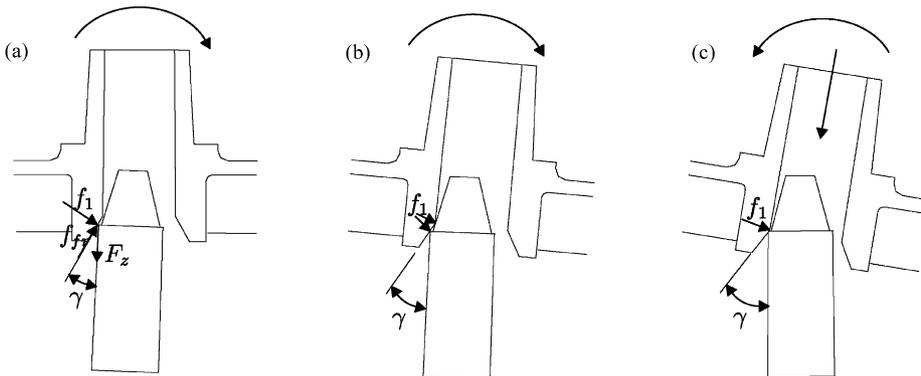


Fig. 8. One side chamfer jamming.

system capable of detecting this situation. Detection is possible by monitoring the contact force during lid assembly. Chamfer jamming detection is threshold triggered when the excessive vertical force is sensed.

## 4. Robot workcell for automatic lid assembly

In accordance with requirements obtained from the above theoretical and practical investigation, the robot workcell for automatic battery lid assembly was built. The workcell incorporates four main systems: industrial manipulating robot, robot gripper, two lid feeding devices, and a control system. Fig. 9 shows the robot workcell operating in the battery manufacturing plant.

For the lid manipulation task the SEIKO D-TRAN RT 2000 industrial manipulating robot was chosen. It is a fast and precise robot with 4 DOF driven by DC motors. The advantages of the selected robot are its high accuracy (0.02 mm), good repeatability (0.01 mm) and an end-effector speed up to 1600 mm/s. The robot workspace satisfies the requirements for performing lid assembly operation for all the lid types. Its maximum allowed loading in vertical direction with fully extended arm is 35 N.

For lid grasping a special robot gripper was designed, combining the grasping and assembly supervision functions. The lids are grasped by the vacuum gripper described in Section 3.1. The suction cup and the rubber stoppers are arranged on a gripper palm which is mounted to the robot wrist via a force cell. In this way, the vertical contact force during the lid picking up and lid setting is measured. The force cell is based on the foil strain gauge technology and after amplifying it outputs an analog signal proportional to the vertical force and two digital signals that are threshold triggered. Additionally, a vacuum sensor was added converting the vacuum signal into an electrical signal. Thus the quality

of the lid grasp can readily be assessed. All the gripper components: the force cell, amplifying circuit and vacuum sensor are encapsulated into an aluminum housing. The housing is mounted on the robot wrist, while the gripper palm is connected to the force cell by an aluminum rod which is sealed in the housing. In the lower right corner of Fig. 9 the robot gripper is shown during the lid picking-up from the lid feeding device.

Two lid feeding devices were built, each incorporating one lid storage system, separating mechanism and horizontal slider frame. In a storage frame, the lids are grouped in a vertical stack containing a maximum of 35 lids. The separating mechanism mounted at the bottom of the feeder, performs separation of a lowest lid from the stack when feeding. The mechanism consists of two parallel pneumatic grippers which drop lid by lid to the horizontal sliding frame while holding the remaining stack. Afterwards, the sliding frame transports the lid horizontally from below the stack to the robot pick up place. All the parts of the feeding devices are made from aluminum elements, while the movable parts are driven by pneumatic cylinders. The feeding devices are designed in a flexible manner enabling quick changeover when changing the lid type. Both, the slider frame and the storage unit can be quickly adapted to the lid type by adjusting the frame guides which are locked by the breeching mechanisms. Infrared proximity sensors are used on the feeding devices for monitoring the number of lids in the stack, lid presence in the separation mechanism and lid presence in the horizontal slider.

The software for controlling the robot workcell is written in the robot programming language DARL and is running on the robot controller hardware. The robot controller, besides robot motion, also controls the operation of the feeding devices and monitors the feedback signals from the gripper and feeders. Communication with the supervising computer of the production line is based on exchanging digital discrete signals. When obtaining the signal from the supervising computer, signalizing that the battery container arrived at the setting place, one of the feeding devices transports the lid to the picking-up place where it is grasped by the robot arm. The robot arm then brings the lid above the battery container and starts the lid setting procedure. During the lid setting the vertical contact force is monitored and setting is stopped when excessive force is detected. The corrective trial is programmed to overcome the problem of one side chamfer jamming. The robot performs this action according to the Strategy 2 proposed in Section 3.4. Any additional lid jamming after two setting trials is considered as an assembly fault and the error is signalized to the supervising computer and to the operator. In the time frame of 25 s, which is available for the lid assembly operation, the lid is transferred from the feeder to position over the battery
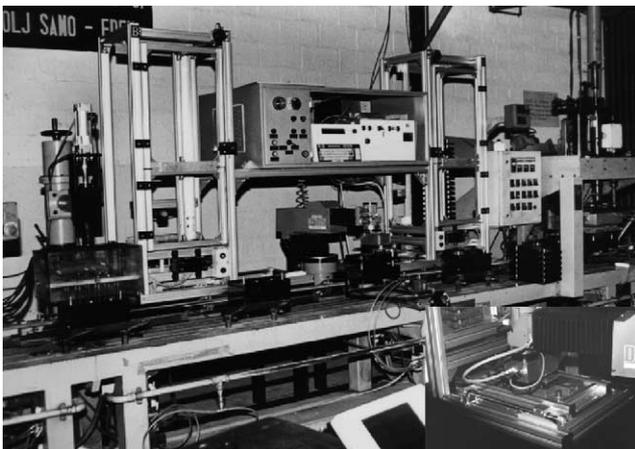


Fig. 9. Robot workcell for automatic lid assembly.

in 10 s. The remaining 15 s are intended for the lid assembly operation. However, lid assembly is normally achieved in less than 5 s. When the lid is successfully placed onto the battery container, the conveyor belt conveys the assembled battery to the next production operation.

## 5. Conclusions

Flexible robot cell performing automatic lid setting operation in the lead/acid battery production process, designed on the basis of thorough theoretical and empirical analysis, was presented. The problem of lid assembly on the battery container was studied from the point of view of a peg-in-hole insertion task. With the help of an experimental assembly setup a detailed insight into the assembly process was gained. Both, single and multiple electrode-in-terminal hole insertions have been considered. Based on derived insertion conditions it was shown that with the single peg-in-hole task the one and two point jamming, and wedging situations are unlikely to occur owing to sufficient clearance between the electrode and terminal hole. The analysis revealed that in real lid assembly, when two electrodes are being inserted simultaneously, more problematical are the events of one side chamfer jamming, causing undesired bending of the lid and bringing the assembly process to a halt.

An approach to overcome the problem was proposed and implemented in the workcell. As already mentioned, the failure rate of the first assembly attempt can vary significantly. The proposed solution incorporating a small size robot and a supervision of assembly interaction force enables multiple and low force assembly attempts. The proposed approach successfully eliminates failures resulting from chamfer jamming without deforming the lid and electrodes structure. However, the human intervention is still required in approximately 1% of cases where the manual electrode bending is needed to continue the lid assembly. Finally, with the application of Strategy 2 in contrast to Strategy 1 the problem of chamfer jamming can be eliminated using a simple manipulator that produces relatively low end-effector forces, thus reducing the cost of automation and still providing required flexibility for a variety of battery types in production. Since the Strategy 2 introduces possible additional robot movement in order to complete the assembly task, the assembly time is slightly prolonged but nevertheless still not influencing the battery production line rate.

For providing feedback information an instrumented vacuum gripper was constructed, capable of monitoring the grasp quality and detecting irregularities during lid assembly. Two special lid feeding devices were also designed, ensuring feeding of five different lid types. One loading of the feeding devices ensures half an hour lid supply at full manufacturing rate. The robot workcell is designed in a flexible manner enabling quick change-over when changing the lid type during production. Utilizing the gripper sensory system, successful lid setting is assured when the position uncertainty of the terminal posts is in the range of the lid terminal chamfers. It must be pointed out that the robot workcell was built for an existing assembly line and therefore integrated into the existing assembly process. It is now successfully operating continuously in three working shifts per day.

For the cost justification of the investment, the operating expense and the system benefits were estimated according to [20]. The costs associated with the workcell installation and start-up are mainly costs of robot and controller (25.000 EUR), lid feeders (5.000 EUR), force sensor (1.000 EUR), vacuum gripper (500 EUR), engineering and programming costs (15.000 EUR), installation costs (5.000 EUR), training costs (1.000 EUR) and insurance costs (2.000 EUR). Total capital investment is estimated to 54.500 EUR. The operating expenses associated with the robot workcell operating in 3 shifts include loading of the lid feeders and adjustment of tools for changeovers (3750 EUR per year), energy costs and spare parts (3000 EUR per year) and preventive maintenance and repairs (600 EUR per year). To determine the planned maintenance downtime, it was assumed that 2% of the operation time per year will be used for maintenance works. Total operation costs amount to 7350 EUR. The immediate system benefits result mainly from the reduction in direct labor. The headcount reduction benefits are furthermore increased because of improved efficiency (25% improvement) and no losses caused by vacations (10% improvement) and absence of health reasons (6% improvement). Total labor cost is estimated to 44.800 EUR for three workers working one per shift. Based on the cost estimates the capital recovery period has been estimated to 1.45 years and the rate of return of investment to 69%. An important advantage of the presented automation is high flexibility of the robot workcell when compared to fixed automatic lid assembly machines available on the market, with no significant difference in the acquisition and start-up costs.

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