Learning skills

Robotics technology in automotive powertrain assembly

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The past 40 years have seen industrial robots establish their superiority over humans in most areas of manufacturing requiring endurance or repeatability. One important application domain, however, has so far lagged behind the industry's expectations: mechanical assembly. As fast, precise and dependable as they are, traditional industrial robots just don't seem able to perform certain assembly operations as well as a skilled human worker.

A task as simple as screwing a light bulb into a lamp socket shows why. Applying the right amount of force and turning the bulb at just the right time, at exactly the right angle, is something a human does intuitively. How can a robot be programmed to do this?

For robots to successfully emulate humans on an assembly line, they need to have force-sensing capability and exhibit compliance. They must be able to direct forces and moments in a controlled way, and react to contact information. New robot force control technology from ABB shows how.

Assembling automotive powertrains is traditionally manual work, performed by skilled, experienced operators. This is because gears and other critical components of the clutches, torque converters and so on, have to be aligned with very high precision in a constrained environment. Such operations, however, take their toll on human labor. Tedious and fatiguing, they can lead to repetitive-motion stress injury as well as lower product quality and efficiency. A robot able to perform at the same level as a human operator would obviously make the prospect of automation in this application area very attractive.

The problem with position-controlled robots

If a position-controlled robot tries to align a pair of gears and its control pro-

gram does not have precise information about the gear-tooth positions, the robot's only option is iterative trial and error, repeated until the relative tooth positions are found. Any attempt by the robot to mate the gears as long as they are misaligned will cause one gear to press hard against the other, generating unacceptably high contact forces. Even if the teeth were chamfered to facilitate mating, misalignment would still produce large side forces as the robot struggled to move the gear along the preprogrammed path toward the centerline of insertion. More than likely, the gears would even jam unless some means of mechanical compliance is provided.

The remote center compliance (RCC) device was developed to solve this problem. Fitted with elastomer shear

pads to reduce the contact forces, it enables an assembly machine to compensate for positioning errors caused by lack of accuracy, by vibration or by inadequate tolerances. As soon as its compliance center approaches the contact point, the (male) part being inserted aligns automatically with the female part by yielding to the high contact forces that are generated by lateral and rotational misalignment. Neither the parts nor the tool are damaged.

Unfortunately, as useful as the RCC device is, it cannot be used for many of the assembly tasks found in an automotive plant. There are several reasons for this. First, the geometries of the assembly parts are complex and vary widely, making it necessary to frequently change from one part-specific device to another. Also, since the device itself is not able to position and rotate the parts relative to each other, assembly takes longer. All in all, there is a higher risk of malfunctioning.

Learning from us

Humans are remarkable for their agility of thought and action when faced with assembling complex parts – applying insertion force where appropriate, yielding before a part becomes jammed. Human assembly workers instinctively learn to make the best use of compliance, sensed forces and moments, and tactile contact clues from edges and boundaries, to quickly obtain the desired result. One feature that clearly distinguishes humans from industrial robots is our ability to sense a contact force and respond to it. For robots to emulate human behavior, they therefore need to exhibit similar force-sensing capability and compliance and be able to direct forces and moments in a controlled way, as well as react to contact information. All of this calls for a change in the traditional robot position control paradigm.

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The ABB solution

As the supplier of the world's largest installed base of robotic products, ABB continuously researches and develops new technology for robot applications. Part of this ongoing activity includes university collaborations, and in one of these ABB scientists and engineers teamed up with researchers from Case Western Reserve University in Ohio, USA, and Lund University in Sweden, to develop a new force/position hybrid platform based on ABB's current S4Cplus robot controller. Around the same time the team also began collaborating with Ford Motor Company to learn more about the specific application requirements. This project yielded a general solution for force control-based assembly applications.

The outcome of this work is a solution that makes ABB robots 'sensitive' as well as powerful. What is more, this new sensitivity is gained without any loss of existing capability or functionality. Hallmark features of ABB robots – advanced control for fast

acceleration, enhanced communication and high reliability, to name a few – are all retained.

The technology was initially tested on IRB4400 and IRB6400 robots, with payloads ranging from 30 to 200 kg, used to assemble different automotive powertrain parts. These tasks, which can be considered complex, included inserting forward clutch hubs and the assembly of F/N torque converters ◼. The tests demonstrated consistently superior performance in terms of cycle time, acceptable insertion force, reliability and ease of programming.

Harmonious position and force control

While the literature on robot force control is formidable, the results have generally been less than impressive. Achieving acceptably fast robot movement while assuring contact stability has persisted as a challenge. Many promising intelligent-control methods have been investigated, but superimposing slow force control on position control has typically resulted in poor performance.

The concept of impedance and admittance[1] is also helpful in understanding force control in a robot. Along each degree of freedom the instantaneous power flow between two or more physical systems can be defined as the product of two conjugate variables, an effort (force) and a flow (velocity). An obvious but important physical constraint is that no one system may determine both variables. Along any degree of freedom a manipulator may exert a force on its environment or impose a displacement or velocity on it, but it may not do both. Thus, an assembly robot should have the property of admittance, accepting force (input) and yielding motion (output). The understanding is that once contact force is sensed during assembly, the robot's motion should be changed in a controlled manner so as not to further increase the contact force.

Using the concept of maximum achievable passive admittance as a foundation, ABB's engineers constructed intelligent control methods that integrate seamlessly with existing advanced position control methods and guarantee stable, gentle contact in most common production environments. The design also ensures a smooth transition between the force control and position control modes.
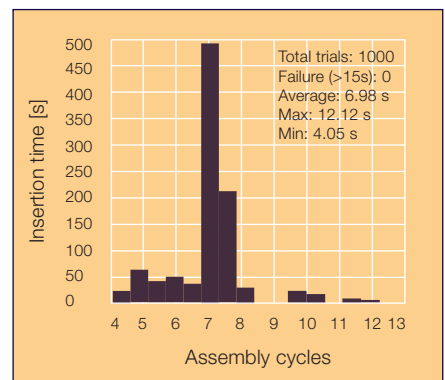
Easy to program

Although a robot with active force control has the advantage of being versatile and programmable for different applications, it requires a more advanced control system and adapted programming to specify how the robot should interact with external constraints. Research so far has focused on the control strategy and its capacity for enabling the robot to establish stable, gentle contact while interacting with the environment. At present, there exists neither a high-level programming language nor a suitable programming concept with which to exploit the force control capability.

Introducing force feedback only enables an industrial robot to respond to an environmental force. In no way does it tell the robot how to move when mating parts. A force control enabled compliant robot can therefore only try to avoid high contact force; it lacks a mechanism for mating parts,

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[1] In force control, the relationship between force and velocity is very important as a means of understanding system behavior in terms of stability and performance. The impedance is defined as force divided by velocity, while admittance is its inverse.
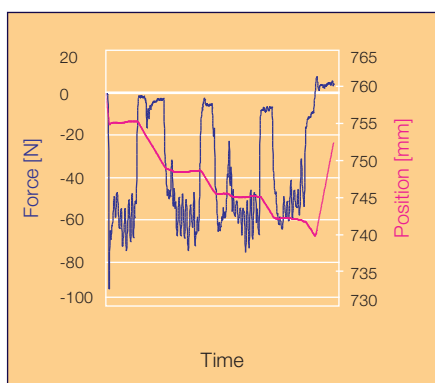
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such as gears, according to their geometrical contours. Jamming of the assembly pieces is prevented, but no help is provided with aligning them. The presumption that a robot's position can be modified via the interaction forces is difficult, if not impossible to put into practice when mating uncertainty is high and there are so many possible contact scenarios that they are mathematically impossible to handle.

The ABB solution relieves users of the burden of complex programming by introducing the concept of attraction force. Coupled with admittance-based fast force control, this ensures not only that contact is made gently, but also that the part being mated is positioned for accurate alignment. As soon as all the alignment requirements are satisfied, the robot can begin its part-specific search and execute the assembly. A typical assembler program could look as simple as this:

Set attraction force;
Set search parameter;
Set destination;
Move to start point;
Activate force control;
If contact
        Activate search;
Endif
If destination is not reached
        Keep searching;
Endif
Deactivate search;
Deactivate force control;
Restract

2	Assembly force for a forward clutch with advanced force control

3	Cycle time statistics for F/N torque converter assembly with an IRB6400 robot with vacuum gripper

Strength plus agility

Clearly, the lighter the parts being assembled, the easier it is to apply just a slight contact force. This is even true for manual assembly. When assembling heavy parts it is no easy matter to limit the allowable contact force to less than the weight of the part being moved into position, as it requires the operator to support that part, against the force of gravity, while going through the assembly steps. The work can be tricky as well as backbreaking.

4	Application map for advanced force control in the automotive industry

Powertrain assembly

Engine
- Bearing Installation
- Bearing liner Insertion
- Gear pump assembly
- Piston assembly
- Spark plug assembly
- Valve Insertion
- Reverse servo installation

Trans/gearbox
- Bearing Installation
- Bearing liner Insertion
- Clutch plate assembly
- Forward clutch hub assembly
- Splined shaft insertion
- Sun gear assembly
- Torque converter assembly
- Transmission accumulator assembly
- Transmission differential assembly
- Triple clutch assembly

Cylinder head
- Bearing Installation
- Bearing liner Insertion
- Cylinder head assembly

Axle
- Bearing Installation
- Bearing liner Insertion
- Planetary carrier assembly
- Planetary pinion insertion
- Splined shaft insertion
- Sun gear assembly

Misc.
- Bearing Installation
- Bearing liner Insertion
- Piston assembly

An example is the assembly of Ford's F/N torque converter case, which weighs about 25 kg. Inside this case is a double splined gear-set into which a pump gear has to be inserted. The pump gear seal is critical and great care has to be taken to ensure it is not damaged in any way during the insertion. An internal splined shaft has to be fitted at the same time, complicating the assembly.

ABB's robotic solution for this task started with the choice of robot, an IRB6400. This was selected on the basis of its payload capacity of 150 kg – the weight of the parts it can support, without help, and without contributing to any undesirable contact forces. Tests showed that the IRB6400 is able to handle a total weight of 75 kg (the combined weights of the part, gripper, force sensor, etc) and still limit the contact force to less than 200 N.

Advanced force controlled ABB robots, as the tests demonstrated, are capable of extremely delicate assembly operations, even when heavy parts are involved. Arm movement is 'feather-light' but still powerful, a combination that suits assembly applications in a wide range of industries.

Superior performance, reliable operation

The tests carried out with advanced force control in the automotive industry have convincingly demonstrated its ability to improve cycle time and agility in different assembly applications. In one application involving the insertion of a forward clutch [2], a work cell with an IRB4400 robot averaged 5.7 seconds for the insertion with a reaction force of less than 100 N on initial contact and under 80 N during assembly (performed manually, insertion typically takes 15 to 20 seconds). In another, F/N torque converters were assembled in an average time of 6.98 seconds with the contact force limited to 200 N [3]. Here it is worth noting that, in addition to the part itself weighing about 25 kg, the allowed positional tolerance was +/–2 mm.

ABB's S4Cplus robot controller is acclaimed throughout the manufacturing industry as the most reliable on the market today. The add-on force control option was developed to enhance this reputation. Leaving nothing to chance, its supervisory functions also monitor the robot for potential sensor error and communication error in addition to the possibility of operational error.

Tests carried out with advanced force control in industry have demonstrated its ability to improve cycle time and agility in different assembly applications.

Benefits for a broader market

Developed primarily for assembly applications in the automotive industry [4], advanced force control has potential benefits for many other areas of industry. Quick market acceptance is expected, especially where absence of the 'human element' in mechanical assembly – the ability to 'get it just right, first time' – has been a problem in the past. In bringing this innovation to market, ABB is once again underscoring its position as the industry leader in robotics technology.

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