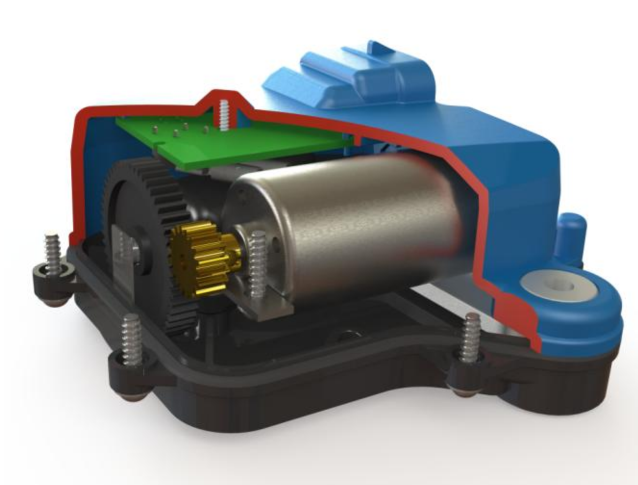
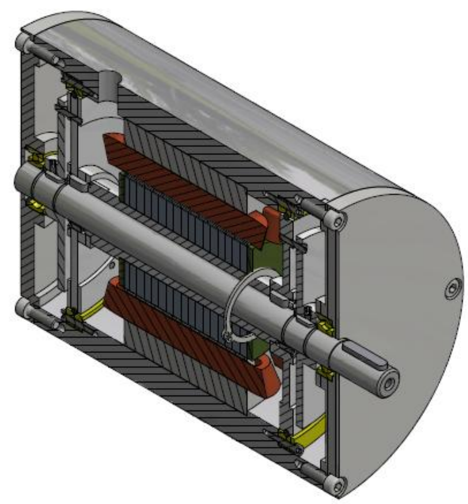
System integration of actuator in AT Shift-By-Wire system





Project within automotive driveline sector

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Content

FFI in short

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1. Executive summary

This project has been performed by Kongsberg Automotive (KA) together with Lund Tekniska Högskolan (LTH) and SME partners BEVI and MagComp. The goal was to develop a competitive and unique SbW system suitable for automotive automatic transmissions (AT). The main objective of this project was to approach AT SbW technology from a system perspective focusing on subsystems where the current state of knowledge was low. To summarize, three main components constitute an AT SbW system: gear shifter unit, electronic control unit and transmission actuator. The largest gap found was lack of a mechanical solution for gear shifting actuator and its electronic control unit (ECU) for which the most efforts in this project was concentrated on.

Actuator concept work was divided in two paths: *Novel* and *Conventional* (state-of-the-art). *Novel* concept was planned to be designed in a very unique way with solutions of high-tech level giving Swedish automotive industry lead on the SbW market even if technology used was not ready yet for mass production.
Conventional concept, on the other hand, was focusing on available technologies in order to create an actuator which could be finalized for production in near future.

The work on *Novel* solution was mainly performed by LTH, BEVI and Magcomp using a scientific approach to the problem. Their work was focusing on 3 technology solutions:

1. Direct electromagnetic actuator based on magnetic memory materials and magnetic interaction of magnetic shear forces like in a conventional rotating machines.
2. Integration of an electromagnetic actuator into a harmonic gear by taking advantage of compression and repulsion forces.
3. Integration of an electromagnetic actuator into a cycloid gear by taking advantage of compression forces.

The first two technologies were soon found to be not suitable for the application either by being too heavy and bulky or too difficult to make work caused by material constraints. After a while, main focus was put on using direct magnetic relocation of the cycloid disc in a cycloid drive. Several concepts were established which differed mainly in concept for gear solution. In the end, one which was found most promising was the one using friction in a cycloid gear for transmitting the force developed in a 12 coil electromagnetic drive to actuator's output shaft. The working friction was accomplished by o-rings being compressed between stator and rotor. Furthermore, an Oldham coupling was used for transforming the force build up in cycloid drive into the axial rotation. A prototype having this solution was made and tested in the laboratory. The highest torque measured was of interesting level but it required substantial current consumption giving too low conversion rate between electrical power put into the system and its output mechanical power compared to its size. A short conclusion was that better efficiency is needed if this concept shall be commercialized in the future.

The work on *Conventional* actuator solution and the ECU needed for driving the actuator in safe and requested way was performed mainly by KA. It was decided very soon in this work that power source would be a standard brush DC motor of a smaller size in order to meet low cost, weight and volume density requirement stated in the project. On the other hand, small motors can deliver relatively low torque. Therefore, the motor selected in the project was complemented with three different folded gears in row giving a high reduction rate. In that way, actuator could achieve enough of output torque to operate gear shifting in an automatic transmission for passenger cars. This gear system was designed with very few components packed in such a way that volume used was as small as it just could be. After the concept definition and development a fully functional prototypes were made and tested both in laboratory and on field while being installed in a demo car. The results from these tests were very satisfying indicating that this actuator would not just meet the market requirements but it also has a superior performance compared to existing SbW actuators on the market. Eventually, this gear system was found to be quite unique and for that reason KA applied for an international patent.

Except finding the right concept for the actuator, a lot of work was also put on designing the ECU for the system. Safety standard ISO26262, which is a market standard, was used as a reference document for defining the concept for HW/SW design resulting in ECU meeting the market requirements regarding the safety and availability. This was first time to do such a work at KA which will help the company in all future projects.

Last but not least, KA has already experienced some market interest for this system giving a big hope that it could be commercialized in a near future.

2. Background

A key trend in the automotive industry is the replacement of traditional control systems based on mechanical or basic electrical interfaces with so called X-by-Wire (XbW) technology incorporating various electromechanical transducers, sensors and sophisticated electronic control systems integrated with human-machine interfaces (HMIs). Automatic Transmission (AT) Shift-by-Wire (SbW) technology enjoys a significant and increasing market penetration, a trend motivated by a number of fundamental drivers such as:

- **Improved packaging**
- **Reduced cost**
- **Improved safety**
- **Improved comfort and ergonomics**
- **Improved fuel economy and reduced emissions**
- **Adaptable driving experience**

3. Objective

The project objective is to collect knowledge and develop competitive actuation subsystems within AT SbW technology which can be commercialized by KA as a tier 1 full system supplier securing the position of the Swedish automotive industry. In addition, the academic partners will through this project be able to develop and direct its expertise directly into an industrial setting, and will strengthen its ties with the Swedish automotive industry while expending their knowledge within electromagnetic actuation.

4. Project realization

The overall strategy of the project realization is defined in figure 1. The basic components constituting an AT SbW system are given; actuator, electronic control system and shifter unit/HMI. Today, the majority of competence in the Swedish automotive industry is centered on the traditional gear shifter unit and its implementation in a vehicle. However, at the other end, actuators for the transmission unit constitute an area where insufficient knowledge has been established. Furthermore, the associated electronic control system facilitating communication between shifter and actuator to ensure a safe and pleasant driving experience is a core field. Indeed, increased knowledge in electronic control systems was needed to realize full system integration.

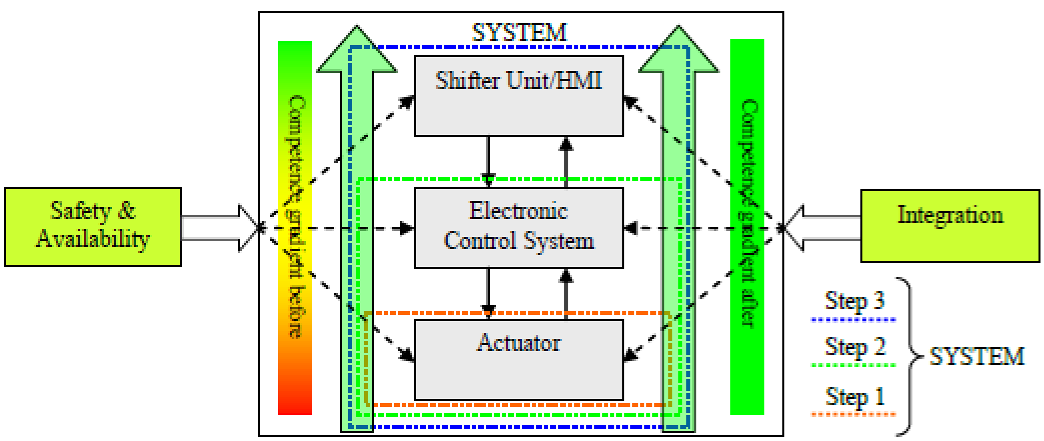

Figure 1. Schematic illustration of project strategy illustrating the nested bottom-up approach and elimination of the competence gradient at systems and subsystems level, thus realizing full AT SbW system competence.

The project got also support from Volvo Car Corporation in terms of sharing their system requirement specification for AT SbW system. The system was finally implemented in a demo car (model V60) for testing and demonstration of the system.

Actuator development work

The plan for this work was to design and make two actuator concepts; one high risk approach (novel) and a corresponding low risk approach (conventional).

Novel solution should have a radical approach to the problem using high-tech solutions never being used before. The goal was to get a solution which could take Swedish AT SbW industry to another level in the future. For that reason, cooperation with some experts was established. LTH University and their *Industrial Electrical Engineering and Automation* team was engaged to lead research work while SME partners MagComp and BEVI would support with their expertise within magnetic materials respectively electrical drives. KA would use the final concept found and implement it into a SbW system.
Conventional solution, on other hand, was suppose to be based on already available technologies which could be commercialized in near future giving Swedish AT SbW industry a foundation to build on. KA was primary partner driving this work.

Novel actuator

3 technology solutions were found for investigating and evaluation:

1. Direct electromagnetic actuators based on magnetic memory materials and magnetic interaction of magnetic shear forces like in a conventional rotating machines.
2. Integration of an electromagnetic actuator into a harmonic gear by taking advantage of compression and repulsion forces.
3. Integration of an electromagnetic actuator into a cycloid gear by taking advantage of compression forces.

The deeper study for the magnetic memory material properties and the design of suitable magnetizer showed that the magnetizer becomes too large and the performance does not meet the specification requirements due to change of magnetic properties as a function of elongation and high temperature dependence of the material. On the other hand, direct electromagnetic actuator was fully possible to provide the desired peak torque without becoming huge and bulky. At the same time this solution was far from being cost optimal for this application.

Integration of harmonic drive unit into electromagnetic actuator was another interesting option for ATSbW application due to its compact and lightweight nature combined with high gear ratio. Unfortunately, early study was indicating that making a harmonic gear for this kind of application would be very difficult to carry out. Materials and components available for making the flexible spline of the harmonic gear were constrained limiting the possible design solutions.

Similar to harmonic gear the cycloid gear makes high gear ratio possible. The advantageous features for cycloid drive are that the unit can be more compact and

efficient compared to the corresponding harmonic gears. Also, its nature is less complex using rigid bodies instead of flexible spline. This type of gear was found most promising and was chosen to proceed with. However, cycloidic “rolling” was needed to be converted to a normal rotary motion. Conventional solution for this is making cycloid cogwheels supported by a crankshaft in center and rotary output shaft connected to the gear by a coupling. Drawback with this solution is an expensive force management making it not that competitive for this type of application.
Therefore, the goal for this work was to make a cycloid gear and the coupling using few and simple parts. After several concepts investigated, the final solution developed had an electromagnetic power unit built of 12 coil stator and a steel core rotor. The cycloid gear was designed with two separate friction wheels attached to the rotor on each side. These wheels were supposed to roll and press against the housing wall and build up enough friction in order to rotate output shaft with desired torque when rotor was excited by the electromagnetic stator coils. Two different prototypes of friction wheels were designed and made (see figure 2).

Figure 2. *Left* Wheels with o-ring in a slot; *Right* Friction wheel coated with friction material.

However, output shaft on the actuator was supposed to deliver rotary torque thus the force achieved in this cycloid gear was needed to be converted. Two couplings were suggested and made for this purpose, i.e. pin respectively Oldham coupling (see fig 3).

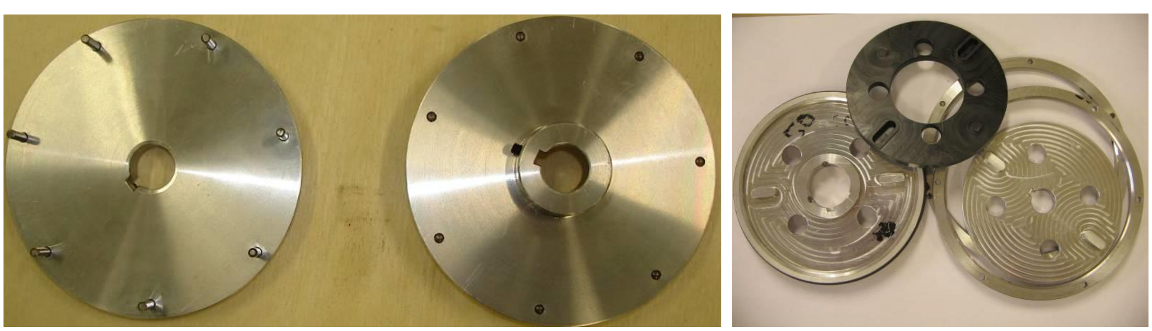

Figure 3. *Left* Pin coupling; *Right* Oldham coupling.

Using these friction elements and couplings, it made it possible to exclude need for expensive crankshaft, ball bearings and cogwheels.

Conventional Actuator

This work was initiated with investigation of what type of power source could be best for this application. Brush DC motor was found to be most suitable in terms of size vs. performance and also price as far as standard design was used. Collaboration with few well known suppliers was established providing the project with samples having performance defined in the project. These samples were then evaluated and the one which become selected in the end was from Johnson Electric with following appearance and performance.

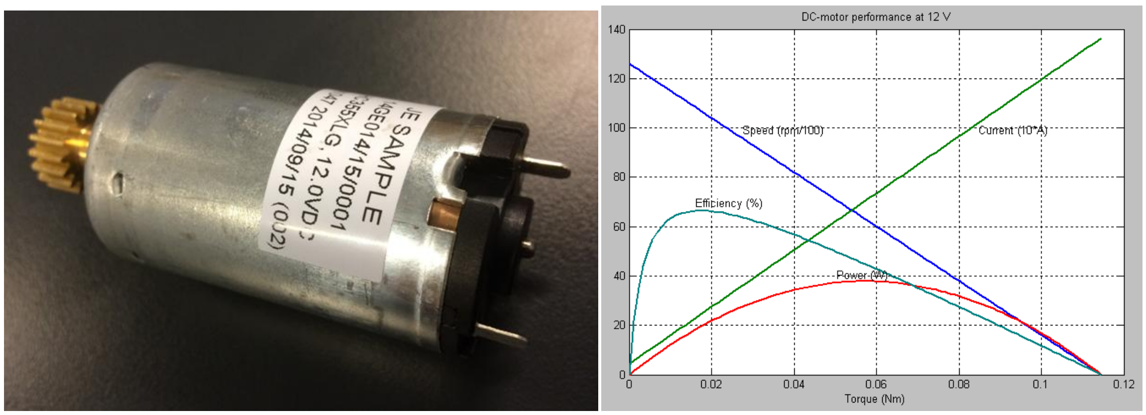

Figure 4. JE DC motor sample and its performance chart.

However, this motor could only achieve a maximum torque of 0,117Nm. Torque required for shifting gears in automatic transmissions could be up to 10Nm. For this reason, design work for this conventional actuator was preceded with making a gear system which could power up performance of the DC motor used. Worm gear is a type of gear which gives high reduction rate and it was found natural to work with that. However, using just one worm gear was not enough in order to get reduction rate needed. So, the concept work ended up in a gear system of three gears giving a gear train of a desired reduction rate. It was also important to meet market requirements in small size, low weight and low cost putting effort on making those gears of as few components as possible and packed as much as possible.

The final concept design (see figure 5) is described below:

1. *Primary Gear*: this gear gives initial reduction rate of 2,9 and couples the motor to the main gear while relieves motor from any axial load making motor design less expensive. Also, this solution locates the main worm gear next to motor for compact design.
2. *Main Gear*: this gear gives reduction rate of 12,5. This type of worm gear is so called “face gear” which is more compact then a traditional worm gear. Also, direction of worm wheel teeth makes this type of worm gear easier to manufacture resulting in lower cost.
3. *Final Gear*: this gear is little bit special where pinion and spur gear have been designed with variable radius giving reduction rate between 6 and 11 because of that. The reason for this solution was to get torque boost in parking position and high speed toward drive position which are performance extremes for this type of application. This solution was found unique and is one of main claims in patent applied for the product.

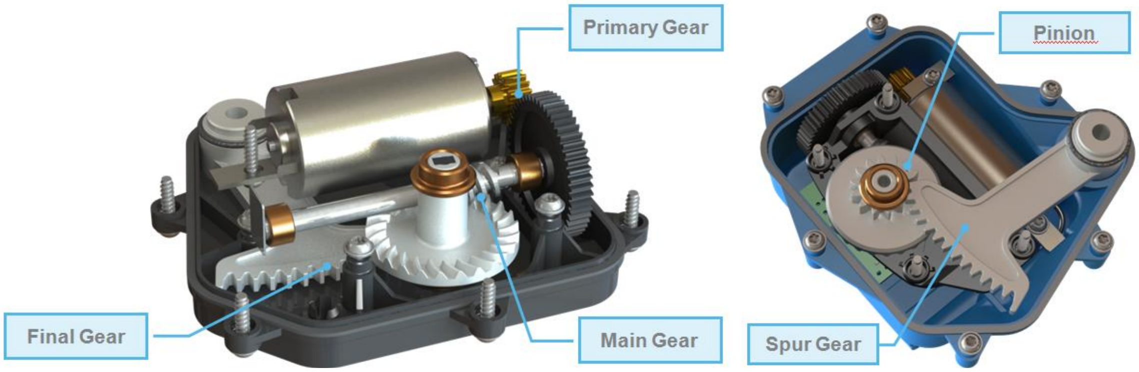

Figure 5. ***Left*** **Overview of actuator gears;** ***Right*** **Final gear design.**

Electronic Control System

Gear shifting is classed as one of safety operations in a vehicle and for that reason this function must be performed in a safe way not jeopardizing health of people in and around the vehicle.

The system including actuator, ECU, shifter and vehicle available in the project has been developed according to the ISO 26262 standard for functional safety in vehicles. The documentations that have been performed with requirements for validation and confirmation measures to ensure a sufficient and acceptable level of safety are: Safety Concept, Hazard Analysis and Safety Goals.

The Hazard analysis has been done from the actuator perspective to identify all possible hazards that could be in question when the actuator is involved. The analysis has identified 48 different hazards cases that each has been evaluated towards an *Automotive Safety Integrity Level* (ASIL level). They have been classified according to ISO 26262 with an ASIL level by their corresponding severity, exposure and controllability ratings. From the identified hazards that have an ASIL level A or higher have the different actuator functions merged into Safety Goals. These findings were then used during ECU development.

The final arrangement for electronic components suggested is shown in figure 6. The actuator has an electronic sensor that continuously reports position to the control unit. Software compares position to desired value, and the difference drives a PID-controller that runs the servomotor by means of an H-bridge. A separate supervisory task (red) can trigger an emergency stop by breaking connection from H-bridge to motor. The software is a modular system arranged according to figure 6. In order to raise the abstraction level in the "application program", a hardware abstraction layer has been introduced. This is the row of modules at the bottom of figure 6, encapsulating drivers for PWM-, timer-, A/D converter-, CAN/LIN-hardware. The whole system is governed by a scheduler (red) capable of running several tasks seemingly concurrently. This has been helpful as software modularization comes naturally.

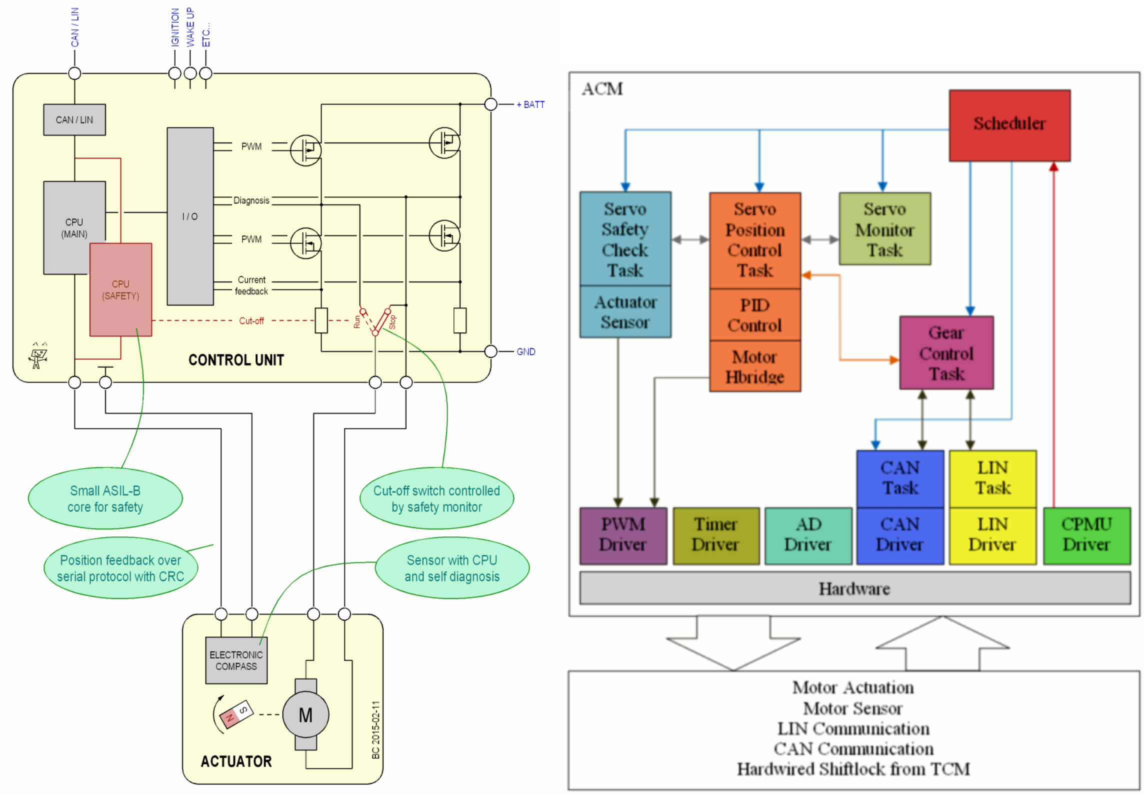

Figure 6. *Left* Principal schematics; *Right* Software modularization

The "application program" has a few blocks/tasks:

1. Controlling servo position using sensor and PID-control is done by the servo task (orange). This block also has a state machine with "ready", "busy" and "error" states, used to discriminate between a moving servo, and one at standstill. This saves current, reduces noise emission and makes time-out monitoring possible.
2. Shift commands are received (on LIN/CAN) from a shift control. They are checked for plausibility and if ok, carried out by the gear control task (purple). This logic does for instance prevent "reverse" engagement when vehicle is at speed, and also prevent leaving "park" unless the brake pedal is pressed.
3. The diagnostic task (light blue) assembles a compound state of signals (sensor, set point, controller state etc) which is analyzed with respect to safety. For instance, velocity in wrong direction must never be detected for a moving servo. There should be neither velocity nor current at standstill etc. In case of error, motor is stopped and system enters "error" state.
4. The diagnostic system compound state is transferred to a separate servo monitor task (light green) which does an independent safety analysis of the system. If anything abnormal is found, motor is separated from H-bridge by tripping the safety switch. By having two independent safety checks like this, a much higher safety class is achieved.

Shifter/HMI

In order to achieve a full AT SbW system a gear shifter unit was needed. This work was supposed to involve significant carryover of existing technology and knowledge available at KA to minimize development time. The activities were focusing primarily on developing new software for the shifter in order to close identified gaps on safety and availability while using an existing SbW shifter from KA.

5. Results and deliverables

The main goal for the experimental evaluation of electromagnetic cycloid drive prototypes was to quantify their torque capability. It would indicate if some of those novel actuators could be implemented in a vehicle or not. Around 10Nm was required for that.
The process of studying the test object was based on determination of torque capability as a function of power supply. Supply current was progressively increased that the outcome of the excited the machine coils resulted in not only the rotor being lifted and able to carry its own weight but also to rotate and lift the external loads. The external load was applied by hanging weights on a wheel 10 cm in radius attached to prototypes output shaft (see figure 7).

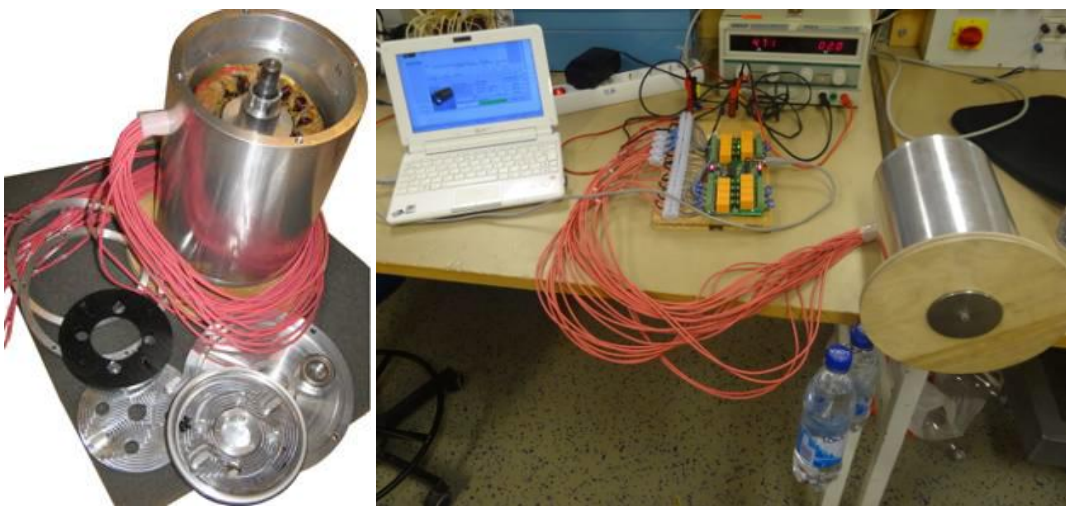

Figure 7. *Left* Novel prototype; *Right* Prototype lifting water bottles during one of torque tests.

Tests were run until actuators stopped rotating, i.e. started to slip. Results from these tests were following:

Proto	Friction wheel	Coupling	Torque per coil ampere
1	Ø3 mm o-ring	7 pins inside round holes	3Nm/5A (2 coils per step)
2	Ø3 mm o-ring	Oldham	3Nm/7A (2 coils per step)
3	Friction material coating	Oldham	1Nm/8A (2 coils per step)

The test results were showing these actuators being too weak and not reaching up to 10Nm. However, it was notified that air gap in prototypes 1 and 2 were larger than planned caused by o-rings not being compressed enough. Outcome of this was weak electromagnetic forces between stator and rotor inside the actuator. Another try was carried out where current supply was increased more and more compressing o-rings until air gap did almost not exist. It turned out to be needed 40A to accomplish this giving maximum output torque 10Nm. This torque performance was found interesting. Unfortunately, 40A of current supply is normally not available in today's cars. Also, this was giving too low conversion rate between electrical power put into the system and its output mechanical power compared to size of this actuator. Conclusion was to not proceed with implementation of these novel actuators in the demo car.

Beside novel prototypes, a prototype of the conventional actuator was built according to design described before. Also, a simple ECU and software for operating basic functions on the prototype were made. By having this simple system, initial tests could be performed giving an indication of the system's potential. And results were promising. Maximum output torque was measured to 17Nm at12V/15A and room temperature. Also, 20 000 of shifting cycling under transmission normal load was achieved, (see figure 8). It was quite clear that this conventional actuator had functionality and performance good enough to be integrated into the demo car, i.e. Volvo V60 with AT transmission.

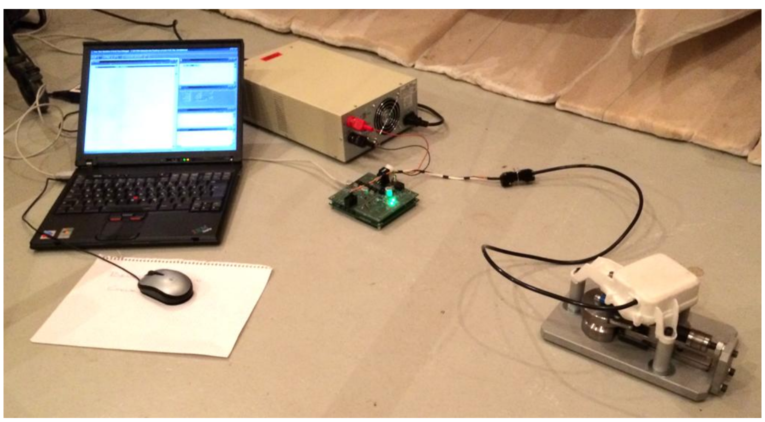

Figure 8. ***Left*** **Cycling test of the prototype system. The actuator is installed on a gear shifting simulation rig and connected to prototype ECU programmed for basic functionality;** ***Right*** **Output torque measurements where actuator was lifting bucket progressively filled with water.**

To be able to do that, ECU with its HW and SW was further developed and made so it could communicate with this demo car and operate the actuator in safe and commended way by the shifter, i.e. driver. In same time, the actuator design was improved and a new prototype was made of materials required for withstanding vibrations and temperatures expected on the demo car transmission. This whole SbW system was successfully installed in the demo car and tested on field. The results were very satisfying. The actuator responded well on drivers inputs putting transmission in right gears every time. All safety functions were also tested with positive results. For instance, the system refused to shift to reverse every time when car was going forward in high speed and driver was commending for that. While allowing the actuator to do so when car was going forward in speed lower then 6km/h which was defined as safe speed for changing car direction.

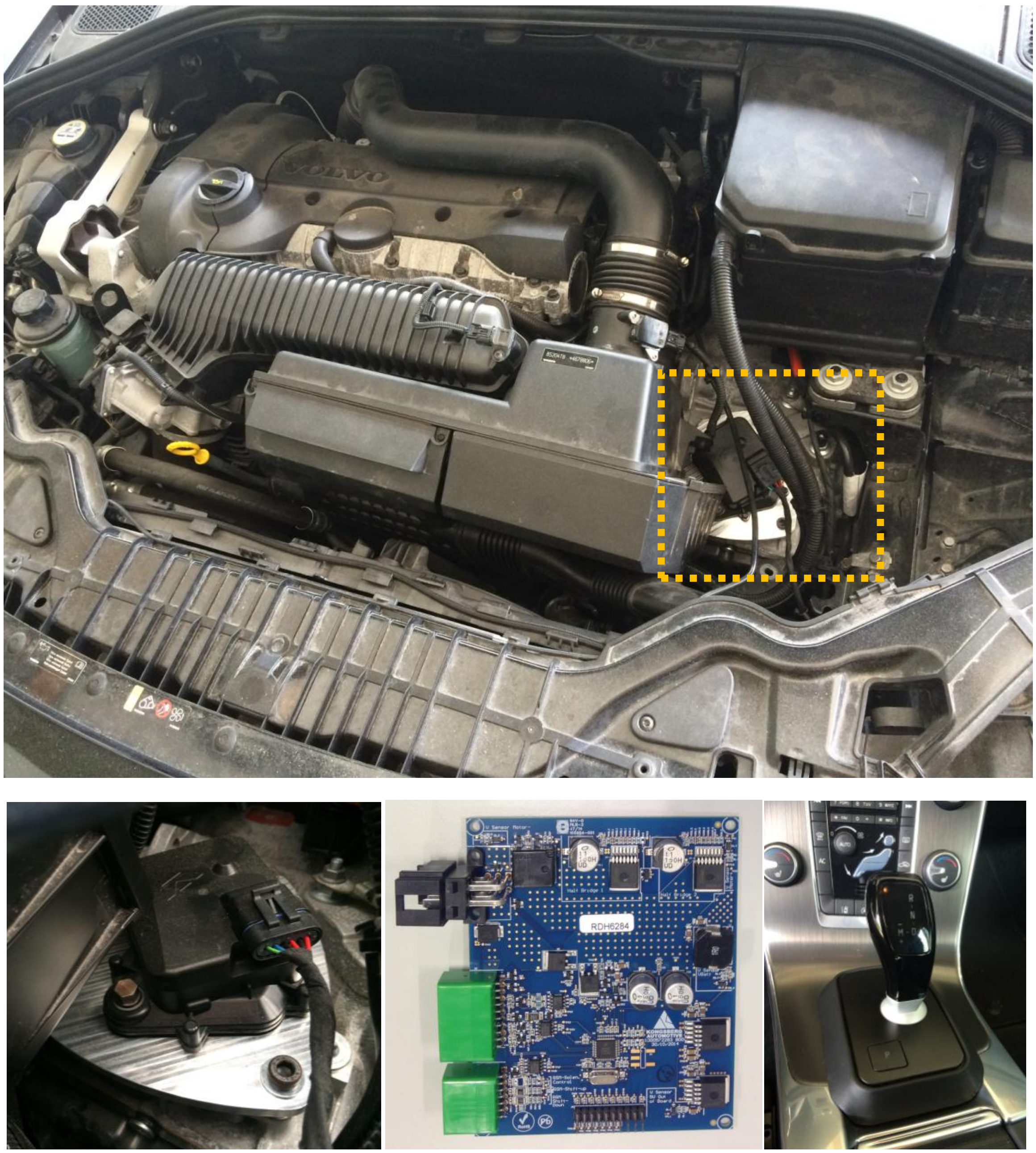

Figure 9. ***Top*** **Actuator installed on the demo car transmission** ***Left*** **Actuator close up;** ***Middle*** **Finalized ECU installed in demo car;** ***Right*** **Shifter installed in center console of the demo car.**

5.1 Delivery to FFI-goals

Collaboration between KA, LTH, BEVI and MagComp have been very successful and strengthened and developed our relationships as members of Swedish industry and educational institution. Our massive amount of research and concept work performed has widened our knowledge about direct magnetic actuation which will benefit our future innovation work. Involvement of these SME partners by making actions in a research project of this size is of great value for their core business which usually can be hard for them to carry out on their own.

Last but not least, the system developed in this project (conventional actuator, ECU and shifter) has demonstrated its advantages in many areas such as performance, safety, availability, comfort and fuel consumption which will certainly improve KAs position on the market as a competitive SbW system supplier. The company has also made a patent (WO 2014082676) for the conventional actuator which concept was found unique and valuable.
The production of driveline products on KA is located in Mullsjö supported by many domestic suppliers which means that Swedish automotive industry will for sure face growth thanks to knowledge collected and products made in this project for this application being more and more demanded on the automotive market. Employment should naturally also be secured.

6. Dissemination and publications

6.1 Knowledge and results dissemination

The SbW system (conventional actuator, ECU and electronic shifter) created in this project has been presented on exhibitions and customer visits. The demo car had been presented as well to partners and potential customers demonstrating KA’s good knowledge within whole SbW technology in terms of technology, safety and HMI.

Except scientific research on senior level, two student groups at LTH were also involved in the project as a part of their course in *Applied Mechatronics*. They got to work with concept validation, analysis and dimensioning of the novel actuator. In this way, knowledge collected within the project could be introduced for academic education. Furthermore, the novel actuator investigations and findings are planned to be presented on one of LTH´s scientific conferences during year 2015.

6.2 Publications

The technical report for novel actuator research work will be published as a public paper on LTH Library database with reference number TEIE-7256.
It is also planned to publish this work in some science magazine during 2015.

FFI

7. Conclusions and future research

The conventional actuator developed and made has truly met all expectations and requirements set up for operating gear shifting on an automatic transmission. Its largest benefits are small size, low weight and first class performance. The actuator is also built of few and simple parts which should result in very reasonable price when it goes in production. Together with its ECU and electronic shifter, a very competitive SbW system has been created giving better and safer driving experience.

When it comes to electromagnetic cycloid drive developed and made in this project, its performance evaluation has shown indications of desirable output torque required for gear shifting on automatic transmission. But to be able to do so, friction management must be solved in better controlled way where air gap between stator and rotor is constantly small giving maximum electromagnetic force inside the drive. Pin and Oldham coupling have been investigated without finding any large difference between them. The performance of the drive is more dominated by the air gap rather than coupling design. So, it needs to be solved in a more efficient way before more investigations are made on coupling design.

8. Participating parties and contact person

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