HYBRID DUAL CLUTCH TRANSMISSION CONTROL:
IMPROVED HYBRID INTEGRATION AND TRANSIENT MANAGEMENT WITH NON-SEQUENCED DCT SOFTWARE ARCHITECTURE

Saurabh Khape, Pedro Zabala

Drive System Design, Leamington Spa, United Kingdom

Abstract: Common software architectures are designed to perform a fixed set of events following a pre-established sequence, usually managed by a high-level coordinator. Sequences are very robust and easy to follow but at the same time are very rigid, making it difficult to handle events such as change of mind in the middle of the sequence or algorithm integration with modern hybrid supervisory modules that may require involvement during part of the sequence. Flexibility to support different levels of functionality on hybrid supervisors is a key factor in the current landscape where powertrains are becoming more integrated than ever, with some vehicle supervisors taking on tasks which are usually part of the transmission control strategy.

This paper will describe a new software architecture developed by DSD with performance examples from an existing vehicle application with hybrid DCT technology. It will be demonstrated how the software can also support AT and off highway power shift technologies with the same architecture, making use of interchangeable "core" modules specific to each technology.

Keywords: Sequenced vs rule-based DCT architecture, Complex change of mind handling, Sharing functionality with hybrid supervisors, Real life examples and extension to non-DCT technology

1. Introduction

With the market being driven by stringent norms around exhaust gas emissions and regulations pushing the market towards e-mobility [1], vehicle manufacturers are being challenged task to develop new low emission and high efficiency powertrain technologies. Coupled with gaining the advantage of being first to market, vehicle manufacturers are set the challenge of cutting down the development times while maintaining quality and flexibility of powertrain architectures. Established vehicle manufacturers are also faced with the added complication of making a smooth transition over to pure EV's from current engine-based powertrains by introducing electrification in stages. While e-mobility technologies mature and become affordable the engine-based powertrains coupled with electrification continue to be the market preferred solution which cannot be ignored.

In order to introduce electrification into their powertrains in stages, vehicle manufacturers are researching a variety of electrified powertrain architectures like MHEV's, self-charging HEV's, PHEV's, direct drive EV's, single speed EV's and multispeed EV's. The aim is to find the best possible solution across the vehicle segments while staying competitive in the market. A vast variety in potential solutions generates strain in the budgets, time, resources, skills and tools required to support advanced and development programs.

The need to produce a custom software solution for every combination becomes a limitation and with new functionality being unlocked by hybrid systems, modifying legacy software may not be feasible. In these conditions, a software platform that is flexible and quickly adaptable with pre-developed standard functionality is mandatory and could be the key for program success.

In the subsequent sections the paper will present the new "Infinite Control" platform; an approach developed by DSD to provide a solution that can address the challenges mentioned above. Among all potential technologies, the paper will focus its scope on DCT (Dual Clutch Transmission) which features a revolutionary "non-sequenced architecture" approach to control. The benefits of this approach of handling complex functionality together with flexibility and adaptability towards hybridisation will also be demonstrated. The paper will illustrate these behaviours via use cases.

2. Industry Challenges

As a company aiming to develop a new product based on DCT technology, the logical approach would be to adapt existing software (if available) to the new application. This approach presents advantages of exploiting verified and validated interface modules used in the existing software. However engineering teams soon discover that legacy DCT software may neither have been designed with enough flexibility to support new functionality of hybridisation (i.e. support to P2 mode transitions) nor be designed to support a variety of architecture options (i.e. P2, P3, P4) and the requirement of complex transients (i.e. change of mind) are still a challenge in a market with growing appreciation for performance and quality.

2.1 Sequence based Control

It is a common practice for control algorithms to be designed to follow a given sequence of events. The software executes actions at every step of the sequence and moves to the next step when certain conditions are met. The sequence is usually managed by a high-level coordinator that commands actions to low level actuation modules. In the case of a DCT, for example, the lower level modules will control gear engagement, clutch torque/slip and power unit intervention.

A sequence based approach has some clear benefits. A sequence is easy to follow, robust, relatively simple to troubleshoot and coordination is guaranteed by the sequence steps.

For DCT applications, the main shifts to handle using sequences described by [5] are as follows:

- Power On Up Shift
- Power On Down Shift
- Power Off Up Shift
- Power Off Down Shift

All shift types share two main phases, a “Torque phase” and an “Inertia or Speed phase”. The shift type will determine which step occurs first. Other sequence steps usually lie before and after these two main phases.

Torque phase: Transferring the torque from the current gear clutch (off going) to the target gear clutch (oncoming).

Inertia phase: In this phase the speed of the input shaft must be synchronised to the input speed required by the target gear. This phase usually involves interaction with the power sources to the driveline (i.e. ICE, E-Machine), which can become more complex with hybridised systems.

The following pictures illustrate the above through a generic description of a Power On Up (Figure 1) and a Power On Down (Figure 2).

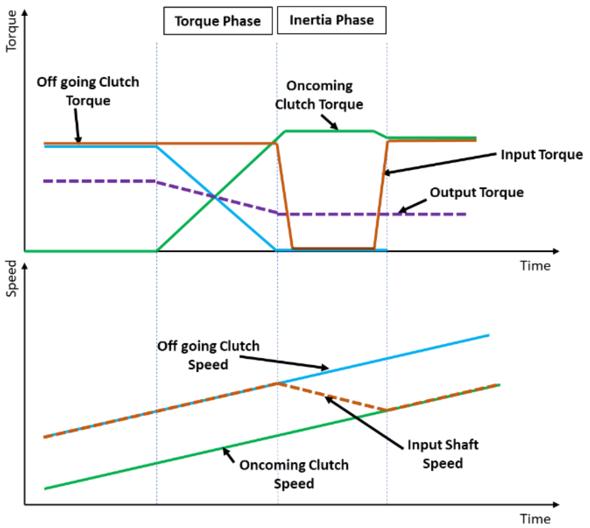


Figure 1: Power On Upshift diagram

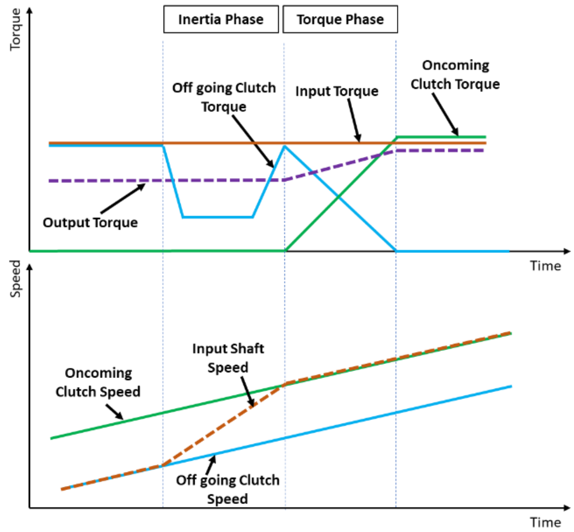
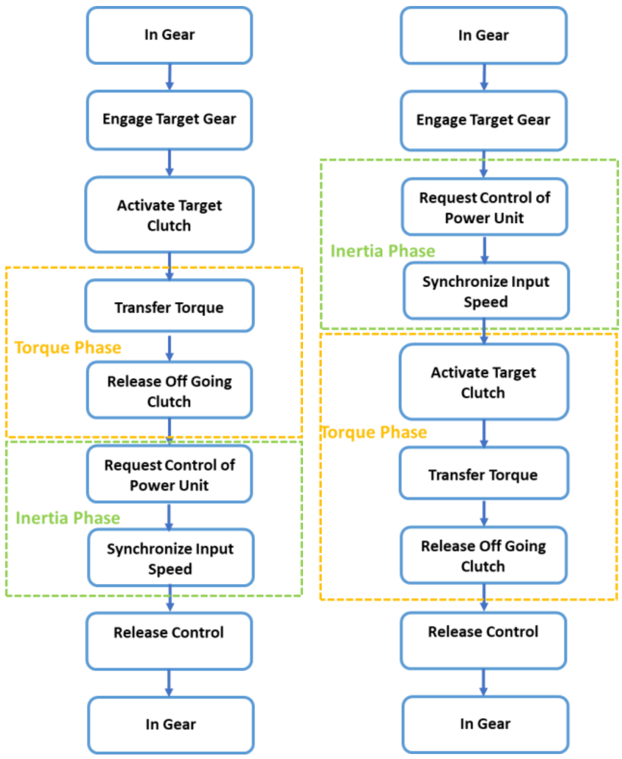


Figure 2: Power On Downshift diagram

The potential sequence steps to perform a Power On Up shift and a Power On Downshift are shown below. Notice how the steps are the same but the order of events in the sequence is different, creating two mutually exclusive sequences.



(a) (b)

Figure 3(a): Sequence for Power On Upshift (b): Sequence for Power On Downshift

2.2 Drawbacks of the Implementation

The sequence based approach though robust struggles with the problem of being rigid. Sequences are usually predetermined to follow a given path/direction from start to finish. Switching between variants of sequences (Power On Up, Power on Down, etc…) or changing the steps to be executed brings great challenges.

An illustration of this is a “change of mind” scenario, when the actions of the driver could require a particular sequence to be abandoned mid-way in favour of a new objective (i.e. target gear is modified mid shift, driver demand – power on-off- changes mid shift).

For example, during a 3rd gear to 4th gear shift process with medium throttle input, the driver suddenly demands 100% pedal; the transmission controller would probably recognise a kick down scenario and changes the target gear to 2nd. If this scenario occurs during the torque phase of the 3rd to 4th power on upshift sequence, the control will have to reverse the torque phase, then switch to a power on down sequence and continue from there (selection of gear, inertia phase, torque phase, etc…). Aborting and switching steps mid-way requires careful transition management of all involved actuations to avoid undesired driveability/shift quality issues.

Though achievable, it can become a real challenge when calibrating transients for all the possible conditions/scenarios that the vehicle is designed to work in, with due consideration to production tolerances.

A common solution is to complete the ongoing sequence and before starting a new sequence to address the change of mind scenario. This would prevent any driveability/shift quality issues that switching sequences could causes but could result in a considerable delay in achieving the outcome desired from driver’s perspective.

The introduction of electrification into the architecture could aggravate the issue even further as functionality becomes even more complex. For example, in a P2 hybrid architecture with DCT; if a change of mind scenario occurs during a driving mode change from pure EV to Hybrid, the driveability could be hugely compromised due to sequence based implementation owing to inability to abort the sequence smoothly and not being able to adapt to the driving mode change.

3. Infinite Control: non-sequenced DCT architecture

3.1 Benefits of Non-Sequenced Architectures

New approaches to software architecture are required in order to overcome the challenges described above and provide upgraded quality and performance.

A new DCT architecture has been developed with self-coordinating independent functions, that perform their activities (torque transfer, gear selection, speed synchronisation, etc…) based on rules and the current status of the system they are designed to control.

By splitting the shift control process into different functions running in parallel and working towards the same objective, the need for a fixed sequence managed by a high-level coordinator, can be eliminated. Each function executes the action which is required to meet the final objective whenever the conditions to do so are met (i.e. to transfer positive drive torque through a slipping clutch, slip must be positive). This guarantees self-coordination of events and, if the final objective is modified, each function will adapt its own targets without having to manage any sequence interruption. This allows for a seamless transient management during shifting and in the “change of mind” scenario.

The architecture of the main software modules is demonstrated in the figure below.

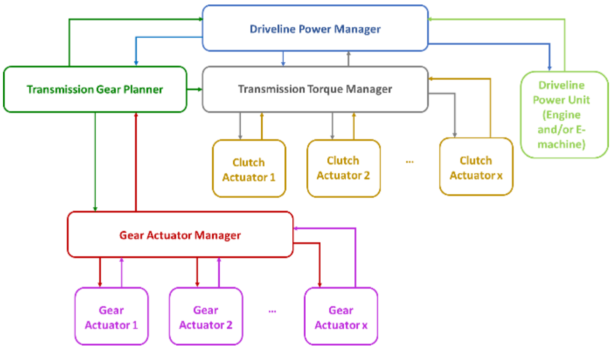


Figure 4: Modular Layout of Infinite Control Platform

Driveline Power Manager module manages synchronisation of the input shaft speed, balancing source and load torques. The Transmission Gear Planner is in charge of monitoring and commanding when and which gear/gears need to be selected while the Transmission Torque Manager monitors and commands the torque required by each individual clutch (torque distribution).

Responding to hybrid functionality becomes natural even outside a shift process. A vehicle supervisory controller will typically request a torque value or slip level at the transmission input that can be easily managed by the Driveline Power Manager, which is the main interface with the power unit. No specific sequence needs to be executed to achieve the necessary target; the control system commands are continuously adjusted towards the desired goal.

3.2 Expanding to platform solutions

As explained above, a non-sequence based DCT implementation makes managing shifts, transitions and hybrid functions smoother, and reduces the calibration complexity and thereby the calibration effort and time.

The benefits of this approach are not limited to DCT technology. Although controlling techniques vary, similar approach can be used for other technologies such as AT, AMT or typical “Powershift” used in commercial vehicles and off-highway applications, and a generic software platform architecture can emerge as a result.

In today’s markets, driven by flexibility, adaptability and speed of response, a full software platform implementing modular architecture with interchangeable modules (based on the technology) is an essential capability for control teams. A platform allows engineering teams to adapt the control system to different technologies with ease, avoiding the need for dedicated software solution for each application under development and accelerating time to market.

This provides vehicle manufacturers with a solution that is flexible and quickly adaptable.

4. Practical Examples

4.1 Example 1: Power On Up Shift

The figure 5 shows a Power On Upshift with the points where each function takes an action based on its vision of the system status.

The shift is triggered by the yellow marker. Until this point, the torque transfer from the power unit to the output shaft is being carried out through the engaged gear and corresponding clutch (C2).

The gear actuator under the Gear Planner will take the following decisions (blue dots) as soon as it is possible:

- engage the target gear
- disengage the previous gear

While waiting, the gear actuator will stay idle. The Torque Manager, knowing that the torque path is required to change from C2 to C1, takes the following decisions (red dots) as soon as it is possible:

- Activate C1
- Perform torque phase into C1
- Deactivate C2
- Support speed phase via C1

While waiting, the torque manager will control the torque on a given clutch.

Finally, the Driveline Power Manager knowing that the input speed is required to change from C2 input speed to C1 input speed, takes the following decisions (purple dots) as soon as it is possible:

- Create a torque imbalance between source torque and load to synchronise the input inertia.

While waiting, the Driveline Power Manager will keep controlling the input speed related to a given clutch input.

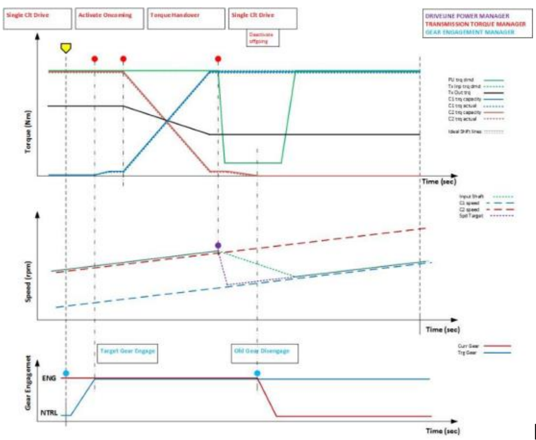


Figure 5: Power On Up shift Implementation in Infinite Control

4.2 Example 2: Change of Mind – abort current request during a torque phase

In this scenario, the system has demanded a Power On Upshift and during the torque phase, the target gear is reverted to the start gear.

The shift is triggered by the yellow marker. Until this point the torque transfer from the power unit to the output shaft is being carried out through the engaged gear and corresponding clutch(C2).

The gear actuator under the gear planner will take the following decisions (blue dots) as soon as it is possible:

- engage the target gear

While waiting, the gear actuator will stay idle.

The Torque Manager, knowing that the torque path is required to change from C2 to C1, takes the following decisions (red dots) as soon as it is possible:

- Activate C1
- Perform torque phase into C1

The Driveline Power Manager is in idle, awaiting to be able to synchronise input speeds to the new gear.

While the torque phase is being performed, the target gear is modified and reverted to the start gear. In other words, the shift has been cancelled.

The gear actuator under the Gear Planner will take the following decisions (blue dots) as soon as it is possible:

- Engage the new target gear (which in this case is already engaged)
- Disengage the previous gear

The Torque Manager, knowing that the torque path is now required to change back to C2, takes the following decisions (red dots) as soon as it is possible:

- Perform torque phase into C2
- Deactivate C1

The Driveline Power Manager which was in an idle state awaiting to be able to synchronise input speeds, receives the new speed target which happens to be the speed the input is at since the shift has been reverted. In this case, the driveline power manager does not see the need to take any action and remains in idle state.

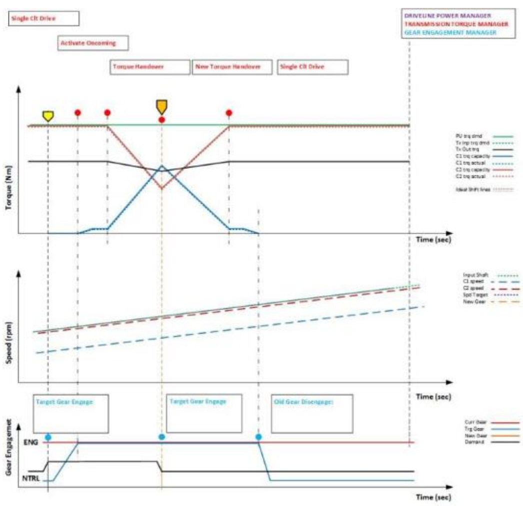


Figure 6: Change of mind shift implementation in Infinite Control during torque phase

4.3 Example 3: Change of Mind – abort current request during a speed phase

In this scenario, the system has initially demanded a Power On Upshift. During the speed phase, the target gear is reverted to the start gear.

The shift is triggered by the yellow marker. Until this point the torque transfer from the power unit to the output shaft is being carried out through the engaged gear and corresponding clutch(C2).

The gear actuator under the Gear Planner will take the following decisions (blue dots) as soon as it is possible:

- engage the target gear

While waiting, the gear actuator will stay idle.

The Torque Manager, knowing that the torque path is required to change from C2 to C1, takes the following decisions (red dots) as soon as it is possible:

- Activate C1
- Perform torque phase into C1
- Deactivate C2
- Support speed phase via C1

The Driveline Power Manager knowing that the input speed is required to change from C2 input speed to C1 input speed, takes the following decisions (purple dots) as soon as it is possible:

- Create a torque imbalance between source torque and load to synchronise the input inertia.

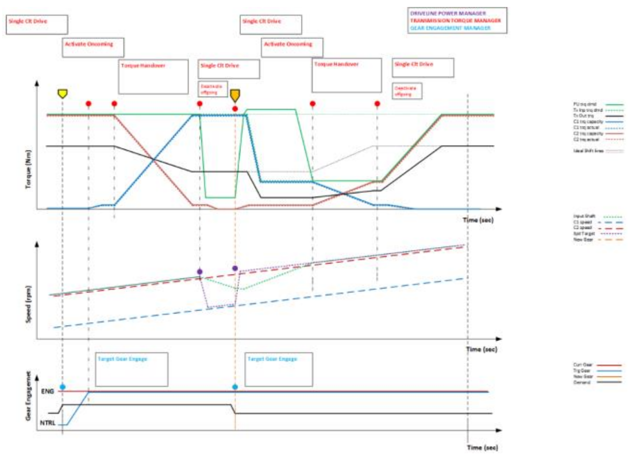


Figure 7: Change of mind shift implementation in Infinite Control during Torque Phase

While performing the speed phase, the gear target changes back to the original gear.

The gear actuator under the Gear Planner will take the following decisions (blue dots) as soon as it is possible:

- Engage the new target gear (which in this case is already engaged)
- Disengage the previous gear

The Driveline Power Manager, knowing that the input speed is required to change back to C1 input speed keeps performing the speed phase action but with a modified target as this is possible straight away.

The Torque Manager, knowing that the torque path is required to change back from C1 to C2, takes the following decisions (red dots) as soon as it is possible:

- Support speed phase via C2
- Activate C2
- Perform torque phase into C2
- Deactivate C1

4. Conclusion

In this technical paper, DSD has introduced the non-sequenced approach to software architecture and demonstrated the benefits that it brings to both, quality improvement during transient management and ease to adapt to electrification needs.

This new approach to software architecture can be embedded into a Control Platform to support the adaptability, flexibility and fast speed to market required in the current markets, heavily driven into electrification by emission regulations.

Through practical examples, typical scenarios to be managed have been presented, and the versatility and performance of the proposed architecture has been shown.

6. References

[1] https://ec.europa.eu/clima/policies/transport/

[2] https://www.magna.com/products/power-vision/product/hybrid-transmissions

[3] https://gknepowertrain.com/en/technology/2016/the-ulimate-edrive-system/

[4] http://www.vocis.co.uk/2-speed-electric-minibus/

[5] Generic control flow for the four types of clutch-to-clutch shifts, Adv Mech Eng 2016; Vol. 8(5) 1-16

[6] Powertrain dynamics and control of a two speed dual clutch transmission for electric vehicles,

7. Glossary

DSD: Drive System Design

DCT: Dual Clutch Transmission

AT: Automatic Transmission

EV: Electric Vehicle

MHEV: Mild Hybrid Electric Vehicle

HEV: Hybrid Electric Vehicle

PHEV: Plug-in Hybrid Electric Vehicle

AMT: Automated Manual Transmission

ECU: Electronic Control Unit

ICE: Internal Combustion Engine