Formal Verification of Twin Clutch Gear Control System

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Summary
Twin clutch model enables the power-shifts as conventional planetary automatic transmission and eradicates the disadvantages of single clutch trans- mission. The automatic control of the dual clutches is a problem. Particularly to control the clutching component that engages when running in one direction of revolution and disengages when running the other direction, which exchange the torque smoothly during torque phase of the gear-shifts on planetary-type automatic transmissions, seemed for quite a while hard to compensate through clutch control. Another problem is to skip gears during multiple gearshifts. However, the twin clutch gear control described in ["M Goetz, M C Levesley and D A Crolla. Dynamics and control of gearshifts on twin clutch transmissions, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2005"], a significant improvement in twin clutch gear control system is discussed. In this research our objective is to formally specify the twin clutch gear control system and verify it with the help of formal methods. Formal methods have a high potential to give correctness estimating techniques. We use UPPAAL for formal specification and verification. Our results show that the twin clutch gear control model partially fulfills its functional requirements.
Keywords:
Formal Specification, Gear Control System, Requirement Verification, Model-checking.

1. Introduction

With the passage of time people become aware about the problematic issues of the automobile, such as environmental pollution, traffic congestion, shortage of resources and the need of new technology is the most important one of them. A clutch is used for gear shifting and it has two main types, i.e., single and twin/dual. The single clutch is used in manual gearboxes while the twin clutch is used in both manual and automatic gearboxes. Twin clutch has two clutches for the gear-shift, one for all odd gears and second for all even gears. Twin clutch model enables the power-shifts as conventional planetary automatic transmission and eradicates the disadvantages of single clutch transmission [7]. In [5], Mecle AB provides the informal requirements and the required information about the environment of a gear controller. Magnus Lindahl et al. show a gear controller application modeled in UPPAL and also verify it. They formalize 46 requirements to check the correctness of the system. The main problem with the twin clutch gear-shift is the automatic control of clutches. Specifically, the absence of one-way clutches (which is clutching component that engages when running in one direction of revolution and disengages when running the other direction), which exchange the engine torque smoothly during the torque phase of gearshifts on planetary-type automatic transmissions, seemed for quite a while hard to compensate through clutch control. Also, the failure to skip gears (i.e. Multiple gear-shifts, for example, from fourth to second gear) without separating the torque transformer clutch was considered a major shortcoming. In the "dynamics and control of gear-shifts on twin clutch transmissions", a significant improvement for both single gear-shift and multiple-gearshift on twin clutch transmission is discussed. The purpose of our research is to discuss and verify thus functional requirements of twin clutch gear control transmission by using formal methods. Formal methods have a high potential to give correctness estimating approaches [3]. We use UPPAAL model checker tool for model checking and verification. A number of automatic verification and modeling tools for real time and hybrid system [4], [6], [8], [10], and [1] have been developed. For the analysis of realistic case study, in [2] a formal method approach has been successfully applied by using the timed automata theory. In [9], UPPAAL model checker is used for formal analysis and verification of agent-based supply chain management system.

The main contribution of this research is a formally described Twin Clutch Gear Control System given in [7] with a set of formal and informal requirements. We prove that the given construction of Twin Clutch Gear Control System doesn't meet all of the functional requirements. Structure of the Paper: In Section 2, we describe the behavior of gear-shift on twin clutch transmission. The behavior of different components involved in Twin Clutch Gear Control System is formally specified and explained in Section 3. Functional requirements are described in Section 4 which are specified as formulas in Section 4.A. Results of model- checking are there in Section 5. We conclude this paper in Section 6.

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2. Problem Description

In this paper, we report an application of the formal description and verification at the design and analysis of control of gear-shift on twin clutch transmission described in [7]. Twin clutch gear-shift consists of several control loops including clutch slip control, engine speed control and output torque transmission control. The gear-shift control initially developed for single up-shifts and down-shifts after that applied for multiple-gearshifts [7]. The control algorithm for gear-shift is divided in two distinctive phases, that are torque phase and inertia phase. During the torque phase, the engine torque is controlled between the clutches and in the inertia phase, the engine speed is synchronized to that of the target gear.

A. Control of Up-Shifts

For the up-shift gear control, the algorithm is shown in Fig 1, In the up-shift gear control algorithm torque phase is followed by inertia phase. To control the power shift in up-shift gear control, first of all we decrease the hydraulic pressure at off-going clutch (step-1) and prefilled the oncoming clutch in step 2. At the off-going clutch the slip controller is activated in step-3 and in step-4 increase the pressure at oncoming clutch. When the pressure is reach zero, deactivate the slip controller and control enter in inertia phase. The speed of the engine is synchronized with the target gear in inertia phase. The engine speed controller becomes activate in step-5 and the output torque controller at oncoming clutch is activated in step-6. At the last, in inertia phase of up-shift algorithm, pressure at c2 become equal to the line pressure in step-7.

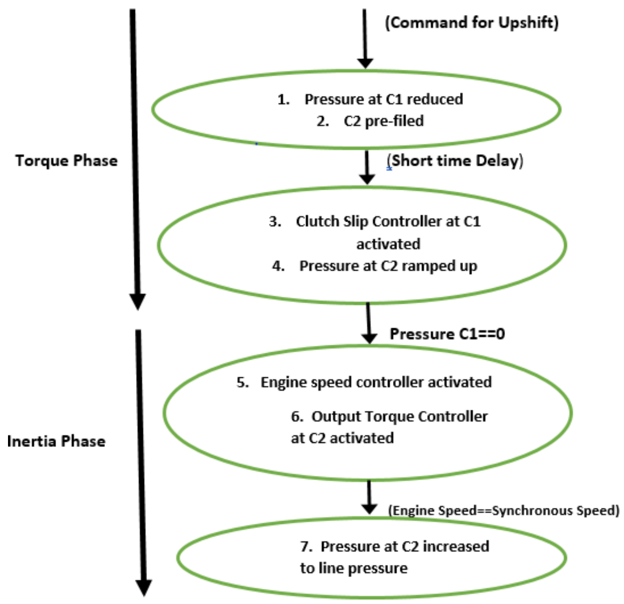

Fig. 1: Algorithm for Up-Shift Control [7]

B. Control of Down-Shifts

The control algorithm for down-shift is shown in Fig 2. In the downshift algorithm, inertia phase is followed by the torque phase. The pressure is decreased at C1 in step-1. The combined effect of the increase throttle angle in step-2 along with the clutch pressure variation due to speed controller in step-3 permit the tracing reference speed without decreasing the too much clutch pressure. Before the inertia phase going to end, pre-filled C2 in step-4 and decrease throttle angle in step-5. For the smooth exchange of engine torque, a clutch slip controller is used in step-6. In parallel with clutch slip controller, the discretionary transmission output controller can be enacted at oncoming clutch in step-7. At the end torque phase of the down-shift algorithm hydraulic pressure at C2 is reached to the line pressure in step-8.

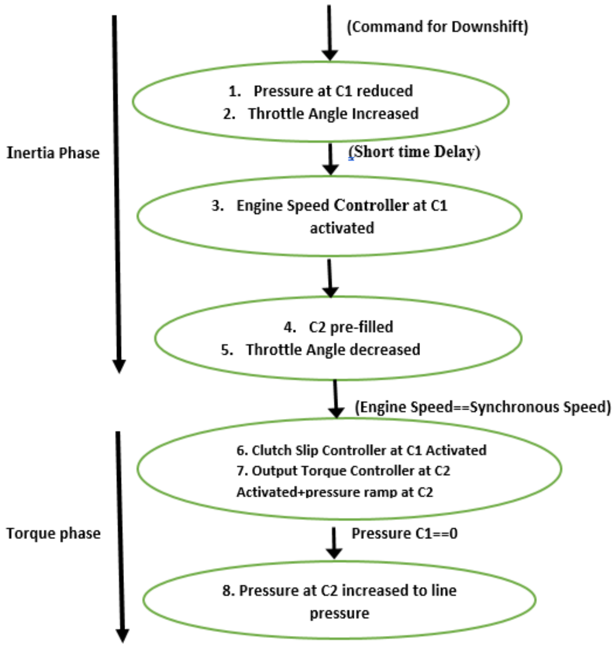

Fig. 2: Algorithm for Down-Shift Control [7]

C. Control of Multiple-Downshifts

The control algorithm for Multiple-downshift is shown in Fig 3. The S1 is the Synchronizer for current gear and S2 is the synchronizer for target gear. The gear-shifts that switch between gears inside a similar portion of the transmission (e.g., from forth to first) can't be proficient as straight forward clutch to clutch shift. Throughout the time-frame where the off-going gear is withdrawn and the on-coming gear connected with the proper portion of the transmission should be torque free. This implies, that both the off-going and the on-coming gear are situated inside a similar portion of the transmission, the clutch that transmitting the torque must be disengaged when the gear change. The result of gear-shift is similar to the manual transmission. In the given algorithm up to step 4 is the same as for single down-shift. The remaining detail is described in [7]. We will give description of the formal model of " dynamics and control of gearshifts on twin-clutch transmissions". We formally verify and specify twin clutch gear control system. The main objective of the case study is to formally describe twin clutch gear control transmissions according to [7] with a set of formal, informal requirements and correctness proof. This twin clutch gear control transmission is verified using the UPPAAL tool set to satisfy the functional requirements of the twin clutch gear control transmission. e.g., there should be no deadlock in the designed system, all gears must be able, it uses clutch for shifting gear. To the best of our knowledge, the correctness of the control of gear-shifts on twin-clutch transmissions is never verified by model checking. So, the research question is the formal analysis of the control of gearshifts on twin-clutch transmissions.

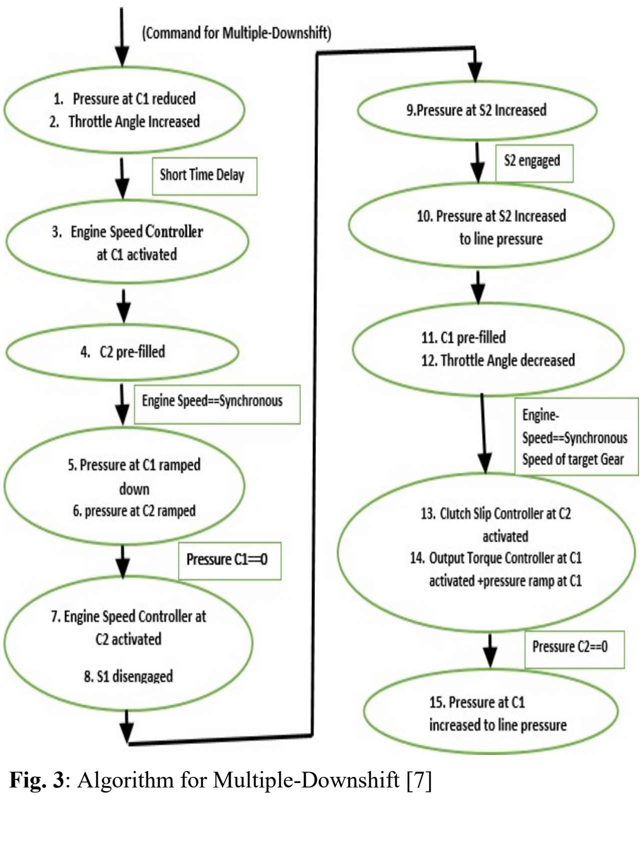

Fig. 3: Algorithm for Multiple-Downshift [7]

3. Formal Specification

In this segment, we describe the brief overview of formal specification in UPPAAL tool. After that we describe the formal specification of the twin clutch gear control system. Our formal specification in UPPAAL cover the following seven participants, and they are Interface, controller, clutch1, clutch2, synchronizer1, synchronizer2 and throttle angle. The main process is the controller. Controller sends and receives messages from other processes for communication. Interface sends request to the controller for gear shift. If controller receives request for gear up-shift or down-shift then it communicate with clutch1, clutch2 and throttle angle process to control the torque and inertia of the vehicle. If controller receives request for multiple gear shift it also communicate with synchronizer1 and synchronizer2. We briefly describe the formal specification of model checking of main processes in our explanation of the system.

A. Model: Twin Clutch Gear Control System

We briefly specify the following concurrent processes of Twin Clutch Gear Control System. We have already described the main functionality of these processes in previous chapters. Now we briefly describe one by one all the above processes

B. Channels in Twin Clutch Gear Control System

Channels are simple processes; we use 54 channels in twin clutch gear control model. These channels are briefly described below.

1) ReqGearUpShift: channel is used to send request from interface process to controller process for upshift the gear.
2) GearUpShifted: channel is used to send the conformation of gear Upshift, from controller process to the interface process.
3) ReqSingleGearDownShift: channel is used to send request from interface process to controller for down shifting one gear.
4) SingleGearDownShiftedchannel: is used to send the conformation of one gear down-shift from controller process to the interface process.
5) TwoGearDownShift: channel is used to send request from interface to controller for two gears down shifting.
6) TwoGearDownShifted: channel is used send conformation of two gear down-shift from controller process to the interface process.
7) ThreeGeardownshift: channel is used to send request from interface to controller for three gears down shifting.
8) ThreeGeardownshifted: channel is used to send conformation of three gear down-shift from controller process to the interface process.

9) FourGearDownShift: channel is used to send request from interface to controller for four gears down shifting.
10) FourGearDownShifted: channel is used to send conformation of four gear down-shift, from controller process to the interface process.
11) FiveGearDownShift: channel is used to send request from interface to controller for five gears down shifting.
12) FiveGearDownShifted: channel is used to send conformation of five gear down-shift, from controller process to the interface process.
13) RequestPresureReduceC1: channel is used to send request from controller to clutch1 process to reduce the hydraulic pressure at off-going clutch.
14) PresureReducedC1: channel is used to send conformation of decrease the hydraulic pressure at off-going clutch, from clutch1 process to the controller process.
15) ReqPreFieldC2: channel is used to send request from controller to clutch2 process to pore field oncoming clutch.
16) PreFieldedC2: channel is used to send conformation of pre-field the oncoming clutch, from clutch2 process to the controller process.
17) ReqClutchSlipControlerActivateC1: channel is used to send request from controller to clutch1 process to activate the slip controller at off going clutch.
18) ClutchSlipControlerActivatedC1: channel is used to send conformation of activation the slip controller at off-going clutch, from clutch1 process to the controller process.
19) ReqPressurC2RampUp: channel is used to send request from controller to clutch2 process to increase pressure at oncoming clutch.
20) PressurC2RampedUp: channel is used to send conformation of increase pressure at oncoming clutch, from clutch2 process to the controller process.
21) ReqEnginSpeedControlerActivateC2: channel is used to send request from controller to clutch1 process to activate engine speed controller at oncoming clutch.
22) EnginSpeedControlerActivatedC2: channel is used to send conformation of activation of engine speed controller at oncoming clutch, from clutch2 process to the controller process.
23) ReqEnginSpeedControlerActivateC1: channel is used to send request from controller to clutch1 process to activate engine speed controller at off-going clutch.
24) EnginSpeedControlerActivatedC1: channel is used to send conformation of activation of engine speed controller at off-going clutch, from clutch1 process to the controller process.
25) ReqOutputTorqueControlerActivateC2channel: is used to send request from controller to clutch1 process to activate the output torque controller at oncoming clutch.
26) OutputTorqueControlerActivatedC2: channel is used to send conformation of activation of the output torque controller at oncoming clutch, from clutch2 process to the controller process.
27) ReqThrottleAngleIncrease: channel is used to send request from controller process to process ThrottleAngle process to increase throttle angle.
28) ThrottleAngleIncreased: channel is used to send con-formation of throttle angle increased, from ThrottleAngle process to the controller process.
29) ReqThrottleAngleDecrease: channel is used to send request from controller process to ThrottleAngle pro-cess to decrease the throttle angle.
30) ThrottleAngleDecreased: channel is used to send con- formation of throttle angle decreased, from ThrottleAngle process to the controller process.
31) ReqPressureC2IncreaseToLinePresure: channel is used to send request from controller process to clutch2 process to increase oncoming clutch pressure up to line pressure.
32) PressureC2IncreasedToLinePresure: channel is used to send conformation of increase oncoming clutch pressure up to line pressure, from clutch2 process to the controller process.
33) ReqReverseGear: channel is used to send request from interface process to controller process for re-verse gear use.
34) ReversedGear: channel is used to send conformation of reverse gear engagement, from controller process to the interface process.
35) ReqPressureC1rampDown: channel is used to send request from controller process to clutch1 process to decrease the hydraulic pressure at off-going clutch.
36) PressureC1rampedDown: channel is used to send conformation of decrease the hydraulic pressure at off-going clutch, from clutch1 process to controller process.
37) ReqS1Disengagechannel: is used to send request from controller process to synchroniser1 process to disengage the synchronizer of original gear.
38) S1Disengaged: channel is used to send conformation of disengage the synchronizer of original gear, from synchroniser1 process to controller process.
39) ReqPressureS2Increase: channel is used to send request from controller process to synchroniser2 process to increase pressure at target gear synchronizer.
40) PressureS2Increased: is used to send conformation of increase pressure at target gear synchronizer, from synchroniser2 process to controller process.
41) ReqS2Disengage: channel is used to send request from controller to synchriniser2 process to disengage the synchronizer of target gear.

42) S2Disengaged: is used to send conformation of dis- engagement the synchronizer of target gear, from synchroniser2 process to controller process.
43) ReqPressureS2increaseToLinepre: channel is used to send request from controller to synchroniser2 process to increase the pressure at the synchronizer of target gear up to line pressure.
44) PressureS2increasedToLinepre: is used to send con- formation of increase the pressure at the synchronizer of target gear up to line pressure, from synchriniser2 process to controller process.
45) ReqC1PreFiled: channel is used to send request from controller process to clutch1 process to prefilled the oncoming clutch.
46) C1PreFileded: channel is used to send the conformation of prefilled the oncoming clutch, from clutch1 process to controller process.
47) ReqClutchSlipControlerC2Activate: channel is used to send request from controller to clutch2 process to activate the clutch slip controller at off-going clutch.
48) ClutchSlipControlerC2Activated: channel is used to send conformation of the activation of clutch slip controller at off-going clutch, from clutch2 process to controller process.
49) ReqOutputTorqueControleC1Avtivate: channel is used to send request of output controller activate at off-going clutch, from clutch1 process to controller process.
50) OutputTorqueControleC1Avtivated: channel is used to send the conformation of the output controller activation at off-going clutch, from clutch1 process to controller process.
51) ReqPressureC1Ramp: channel is used to send request from controller to clutch1 process to increase the pressure at oncoming clutch.
52) PressureC1Ramped: channel is used to send conformation of increase the pressure at oncoming clutch, from clutch1 process to controller process.
53) ReqPressureC1IncreaseToLinePresure: channel is used to send request from controller to clutch1 process to increase the pressure at oncoming clutch up to the line pressure.
54) PressureC1IncreasedToLinePresure: channel is used to send conformation of to increase the pressure at oncoming clutch up to the line pressure, from clutch1 process to controller process.

C. Interface Automaton

The model is initiate from Interface. Initially the request is sent from inter- face to the controller for gear shifting. Controller communicate with all other processes then acknowledge the interface. The following procedure is used in interface automaton.

1) If the gear is zero, then we can only send request for gear up-shift.

2) If the gear is first, then we can gear up-shift and single down-shift.
3) If the gear is second, then we can send request for gear up-shift, one gear down-shift or two gear down- shift.
4) If the gear is three, then we can send request for gear up-shift, one gear down-shift, two gear down-shift or three gear down-shift.
5) If the gear is fourth, then we can send request for gear up-shift, one gear down-shift, two gear down-shift, three gear down-shift or four gear down-shift.
6) If the gear is fifth, then we can send request for gear up-shift, one gear down-shift, two gear down-shift, three gear down-shift, four gear down-shift or five gear down-shift.
7) The reverse gear is only enabled when the gear is zero.

D. The Automaton for Controller Process

Controller is the main process of the model. The controller starts from initial state. It receives command from interface for gear shifting or reverse gear. Gear shifting commands is three types which are gear up-shift, gear down-shift and Multiple gear downshift. Controller receives only one command at a time. Controller communicates with all processes. According to three types of commands for gear shifting, controller is divided in to three loops to complete the task. We briefly explain these loops by dividing the controller in to three parts.

Part-1: The interface sends request for gear up-shift to the controller and then the controller goes to the start phase state. For gear up-shifting, first control the torque of the engine then inertia of the vehicle. Torque phase start from the start phase state, and inertia phase start from Inertial-Phase state. The following procedure is used for gear up-shift.

1) First of all, it reduces the hydraulic pressure at off-going clutch. Controller sends request to clutch1 process to reduce pressure, Clutch1 reduces pressure and acknowledge to the controller.
2) Controller Sends request to the clutch2 process to prefilled the oncoming clutch. Clutch2 process pre-filled the oncoming clutch and acknowledge to the controller.
3) Controller sends request to the clutch1 process to activate the clutch slip controller at off-going clutch. After activating clutch slip controller, it acknowledges to the controller.
4) In forth step controller requested to the clutch2 process to increase the hydraulic pressure at oncoming clutch.

5) To control the engine speed, the controller sends a request to the clutch2 to activate the engine speed controller at oncoming clutch.
6) After engine torque controller activation, clutch2 also send command for to active the out-put torque controller at oncoming clutch. clutch2 activates the out-put torque controller and acknowledge to the controller.
7) when engine is speed equal to the synchronous speed then the controller sends request to the clutch2 process to increase pressure of oncoming clutch to the line pressure. Clutch2 after increasing pressure acknowledge to controller.
8) After above communication the model is able to up-shift the gear, the controller acknowledges the interface that the gear is up-shifted.

Part-2: Control of Single Gear Down-shift Automaton: When the interface send request for gear single gear down-shift to the controller then the controller goes to the start phase state. For gear single down-shifting, first control the inertia of the vehicle then torque of the engine. The inertia phase start from the start phase state, and torque phase start from start rephase state. The following procedure is used for gear downshift.

1) First of all, it reduces the hydraulic pressure at off- going clutch. Controller sends request to clutch1 process to reduce pressure, Clutch1 reduces pressure and acknowledge to the controller.
2) After reducing pressure at off-going clutch. Controller process sends request to the ThrottleAngle process to increase the throttle angle and Throttleangle process acknowledge to the controller process.
3) To control the engine speed the controller process sends a request to the clutch1 process to activate the engine speed controller at off-going clutch. Then an engine speed controller activated at off-going clutch.
4) Controller Sends request to the clutch2 process to prefilled the oncoming clutch. Clutch2 process pre- filled the oncoming clutch and acknowledge to the controller.
5) Then controller sends command to ThrottleAngle process to decrease the throttle angle, ThrottleAngle process decreased the throttle angle as well as ac- knowledge to the controller.

6) When the engine speed is equal to the synchronous speed, Controller sends request to the clutch1 process to activate the clutch slip controller at off- going clutch. After activating clutch slip controller, it acknowledges to the controller.
7) In forth step controller requested to the clutch2 process to increase the hydraulic pressure at oncoming clutch.
8) After engine torque controller activation, controller also sends command to active the out-put torque controller at oncoming clutch. clutch2 activates the output torque controller and acknowledge to the controller.
9) When the pressure at off-going clutch is equal to zero, then the controller sends request to the clutch2 process to increase pressure of oncoming clutch to the line pressure. Clutch2 after increasing pressure acknowledge to controller.
10) After above communication the model is able to one gear down-shift, then controller acknowledge the interface that the one gear is downshifted.

Part-3: Multiple gear down-shift is possible when the engine in second or more gear. If the engine in second gear, then we can two gear down-shift. If the engine in third gear, then we can two or three gear down-shift. If the engine in forth gear then we can two, three or four gear down-shift. If the engine in fifth gear, then we can two, three, four or five gear down-shift. When the interface sends request for multiple gear down-shift to the controller then the controller goes to the start-phase state. The following procedure is used for gear down-shift.

1) First of all, it reduces the hydraulic pressure at off-going clutch. Controller sends request to clutch1 process to reduce pressure, Clutch1 reduces pressure and acknowledge to the controller.
2) After reducing pressure at off-going clutch. Controller process sends request to the ThrottleAngle process to increase the throttle angle and Throttleangle process acknowledge to the controller process
3) To control the engine speed, the controller process sends a request to the clutch1 process to activate the engine speed controller at off-going clutch. Then an engine speed controller activated at off-going clutch.
4) Controller Sends request to the clutch2 process to prefilled the oncoming clutch. Clutch2 process pre-filled the oncoming clutch and acknowledge to the controller.
5) In fifth step controller requested to the clutch1 process to decrease the hydraulic pressure at off-going clutch.
6) After decreasing pressure at off-going clutch, controller requested to the clutch2 process to increase the hydraulic pressure at oncoming clutch.
7) When the pressure at off-going clutch becomes equal to zero, to control the engine speed the controller sends a request to the clutch2 to activate the engine speed controller at oncoming clutch.
8) Controller sends request to Synchroniser1 process to disengage the synchronizer of the original gear.

Synchroniser1 process disengaged the synchronizer and acknowledge to the controller process.
9) Controller sends command to Synchroniser2 process to engage the synchronizer of target gear.
10) When target gear synchronizer engaged then again controller send command to Synchroniser2 to in- crease the pressure at target gear synchronizer to the line pressure. Synchroniser2 increased the pressure and acknowledge to the controller.
11) Controller Sends request to the clutch1 process to prefilled the oncoming clutch. Clutch1 process pre-filled the oncoming clutch and acknowledge to the controller.
12) Then controller sends command to Throttle-Angle process to decrease the throttle angle, Throttle-Angle process decreased the throttle angle as well as ac- knowledge to the controller.
13) When the engine speed is equal to the synchronous speed of target gear, Controller sends request to the clutch2 process to activate the clutch slip controller at oncoming clutch. After activating clutch slip controller it acknowledges to the controller.
14) After engine torque controller activation, controller also send command for to activate the out-put torque controller at oncoming clutch. clutch1 activates the out-put torque controller and acknowledge to the controller.
15) When the pressure at off-going clutch is equal to zero, then the controller sends request to the clutch1 process to increase pressure of oncoming clutch to the line pressure. Clutch1 process after increasing pressure acknowledge to controller.
16) After above communication the model is able to multiple gear downshift, then controller acknowledge the interface that the gears is downshifted.

E. Clutch1 Automaton

Clutch1 process receives the different requests from controller process, it performs action according to receive request at the off-going clutch and respond to controller process. This process performs the following functions and responds to the controller.

1) It reduces hydraulic pressure at off-going clutch.
2) It activates the engine speed controller at off-going clutch.
3) It activates the clutch slip controller at off-going clutch.
5) It activates the output torque controller at off-going clutch.

F. Clutch2 Automaton

Clutch2 process receives the different requests from controller process, it performs action according to receive request at the oncoming clutch and respond to controller process. This process performs the following functions and respond to the controller.

1) It increases hydraulic pressure at oncoming clutch.
2) It activates the engine speed controller at oncoming clutch.
3) It Activates the clutch slip controller at clutch for torque fill.
4) It activates the output torque controller at oncoming clutch.
5) It increases the pressure at oncoming clutch up to the line pressure.

G. Synchroniser1

This process receives request from controller process to disengage the original gear synchronizer. After disengaging the synchronizer, it responds to the controller process.

H. Synchroniser2 Automaton

This process receive request from controller process to disengage the target gear synchronizer, increase pressure at target gear synchronizer and increase the pressure at target gear synchronizer up to line pressure. After doing this function it responds to the controller process.

I. Throttle Angle Automaton

This process receive request from controller process to increase or decrease the throttle angle, after increasing or decreasing throttle angle it responds to the controller process.

4. Functional Requirements

We find out the following requirements of the twin clutch gear control system.

R1: Deadlock freedom. There should be no deadlock in the designed system.

R2: User can use up to five gears.

R3: User can use Reverse gear only when the gear is neutral.

R4: In Single down-shift control when the clutch slip controller is activated at off-going clutch, the engine speed should be equal to synchronous speed.

R5: In up-shift control when the speed controller is activated, the pressure at off-going clutch should be equal to zero.

R6: In single down-shift control when the pressure at oncoming clutch is equal to line pressure then the pressure at oncoming should be equal to zero.

R7: In up-shift control when the pressure at oncoming clutch is equal to the line pressure then engine speed should be equal to synchronousspeed.

R8: If the gear is up-shifted, the torque phase is followed by inertia phase.

R9: If the gear is down-shifted, the inertia phase is followed by torque phase.

R10: User can down shift two gears combine when the gear is two ormore.

R11: User can down shift three gears combine when the gear is three or more.

R12: User can down shift four gears combine when the gear is four or more.

R13: User can down shift five gears combine when the gear is five.

R14: gear can be down shifted one by one.

R15: User can up-shift the gear.

A. Formal Specification of the Requirements

The requirement R1 describes that there is no deadlock in the whole system. The formula is given below.

A[] not deadlock

According requirement R2, there is possible to us from gear one to five gears. Formula for R2 is given bellow

E<> gear<=5

According to requirement R3, the reverse gear is enabled only if the gear is zero. The formula R3 is given below.

E<> (Interface.GearReverse && (Gear==0))

According to requirement R7, during gear up-shifting when the pressure at on- coming clutch is equal to the line pressure then engine speed should be equal to synchronous speed. The formula for R7 is given bellow.

E<> (Controller.PressureC2increaseToLinePressur imply Controller.EnginSpeed==SynchronousSpeed)

According to requirement R8, If the gear is up-shifting then the torque phase followed by inertia phase. The formula for R8 is given bellow.

Controller.startphase-->Controller.InertiaPhase

According to R4 requirement, during single gear down-shifting, when the clutch slip controller is activated at off-going clutch then engine speed should be equal to synchronous speed. The formula for R4 is given bellow.

E<>(Controller.SlipControlActivate imply Controller.EnginSpeed==SynchronousSpeed)

According to Requirement R5, during up-shift gear control when the speed con- troller is activate then the pressure at off-going clutch should be equal to zero. The formula for R5 is given below.

According to requirement R6, during single gear down-shifting when the pressure at oncoming clutch is equal to line pressure then the pressure at oncoming should be equal to zero. The formula for R6 is given bellow.

E<>(Controller.PressureC2increaseToLinePressur

imply Controller.PressureC2==0)

According to requirement R9, If the gear is down-shifting then the inertia phase is followed by torque phase.

Controller.startphase-->Controller.TorquePhase

According to requirement R10, there two gears can be release combine when the gears are two or more. The formula for R10 is given below.

E<>Interface.TwoGear_DownShift && Gear>=2

According to requirement R11, there three gears can be release combine. The formula for R11 is given below.

E<>Interface.ThreeGear_DownShift && Gear>=3

According to requirement R12, there four gears can be release combine. The formula for R12 is given below.

E<> (Controller.SpeedControllerActivate imply Controller.PressureC1==0)

E<>Interface.FourGear_DownShift && Gear>=4

According to requirement R13, five two gear can be release combine. The formula for R13 is given below.

E<>Interface.FiveSGear_DownShift && Gear>=5

According to requirement R14, there gear can be down-shifted one by one. The formula of R14 is given bellow.

E<>Interface.SingleGear_Downshift

According to requirement R15, we can up-shift the gear. The formula for R15 is given bellow.

E<>Interface.Upshift

5. Verification Results

We verify all the above properties by using verifier, verifier is a feature of UPPAAL model checker. For verification of the properties, we write the property formula in query section, after execution the result of the query is displayed in the status section. The results of the requirements are shown in Table 1. We verify our system model for,

Total Number of Processes = 7
Gear Using Limit = 5

Table 1 Verification Results

Requirements	Computational Time	State Space	Results
R1	0.031 sec	644 states	Satisfied
R2	0.016 sec	1 state	Satisfied
R3	0.015 sec	3 states	Satisfied
R4	0.015 sec	1 state	Satisfied
R5	0.025 sec	1 state	Satisfied
R6	0.016 sec	1 state	Satisfied
R7	0.017 sec	1 state	Satisfied
R8	0.016 sec	46 states	Not Satisfied
R9	0.015 sec	70 states	Not Satisfied
R10	0.017 sec	58 states	Satisfied
R11	0.016 sec	129 states	Satisfied
R12	0.017 sec	233 states	Satisfied
R13	0.016 sec	374 states	Satisfied
R14	0.017 sec	138 states	Satisfied
R15	0.016 sec	1 state	

The requirement R8 is violated and not satisfied. According to this requirement, the torque phase must be followed by inertia phase. But there are some situations, in which control can't reach to the inertia phase. Such situation is found when the control enters to the throttle increase loop, the control entangled here and can't reached to the inertia phase. The requirement R9 is also violate and not satisfied, according to this requirement, inertia phase must be followed by torque phase. But there are some situations, in which control can't reach to the torque phase. Control entangled in reverse gear and not reached to torque phase.

6. Conclusion

We formalized Twin Clutch Gear Control System as specified in [7] in UPPAAL model checker. We then formalized functional requirements of the system and verified them using UPPAAL model checker. We also reported some situations with counter examples that were found in our formal analysis.

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