Development of CVT/ECU for Daihatsu Vehicles

Hiroyuki Hida
Yutaka Inui
Junichi Kusumoto
Ryohei Kubota
Yusuke Nishida
Yosuke Taichi

Abstract

Recent years have seen the continued development of fuel efficient and hybrid vehicles that emit reduced levels of exhaust gases, including carbon dioxide (CO_2), due to the increasing demands on the automobile industry for environmental protective measures and improved gas mileage.

In order to provide optimal gear ratios for all driving conditions, a continuously variable transmission (CVT) that allows the engine performance to operate at peak efficiency has been developed that replaces the conventional fixed gear ratio transmissions with a combined planetary gear and torque converter structure.

Mini-vehicles are no exception to such demands and they must satisfy them at a low cost.

This paper discusses a lightweight compact CVT unit newly developed by Daihatsu and an electronic control unit (ECU) developed jointly between Daihatsu and Fujitsu Ten. The paper also introduces an integrated circuit developed in response to a shortened development period by Fujitsu Ten in order to provide lower costs and improved product quality.

1 Introduction

1.1 Background to development of a Continuously Variable Transmission (CVT) system for mini vehicles

Although recent sales of motor vehicles in Japan have been sluggish, sales within the mini vehicle class have gained momentum, surpassing the two million unit sales mark to account for one out of every three vehicles sold overall. Tax advantages that Japanese laws grant to mini vehicles had been a common reason offered for their attraction but recently customers' attitudes have changed with many people giving reasons such as, "I thought it'd make a good second car," or "I wanted my first car to be a mini one." In actuality, current mini vehicles are fully equipped and provide a level of safety that is comparable to compacts in the 1,000 cc class. However, in exchange for this improved performance, vehicle weight has increased and, since the mini vehicle class is limited to 660 cc engines, drivers must push the accelerator pedal further to the floor, leading to the gas mileage of mini vehicles to essentially become comparatively worse than that of compact vehicles.

As crude oil prices continue to rise steeply, mini vehicle manufacturers have an urgent need to focus sales strategies on improved fuel economy. In this regard, the CVT is expected to offer a measure of support in the improvement of gas mileage.

Up to now, mini vehicles have been equipped with either a low-cost manual transmission (M/T) that provides good fuel mileage or a clutch-free, or fixed gear-ratio automatic transmission (A/T) that is comparatively easy to drive. The CVT is designed to be able to offer both the driveability of an A/T together with good fuel economy.

Since the CVT is continuously changing transmission speed there is no loss of drive power during gear shifting and this capability for smooth operation is a distinctive feature of the CVT. Compared to a conventional A/T, the CVT provides a 10% improvement in gas mileage and, depending on the circumstances, it can offer better gas mileage than an M/T. It also provides reduced carbon dioxide (CO_2) levels.

The reasons why the CVT has not previously been common equipment for mini vehicles is the extensive development costs involved as well as the high cost of the CVT main body. In addition to the unavoidable problem of low cost, a CVT must be small-sized and low-weight in order to be suitable for equipping to mini vehicles.

Daihatsu developed and equipped a CVT as standard equipment to their "Sonica" model that went on sale in June of 2006 that, with the help of various efforts and strategies, has managed to satisfy the exacting requirements mentioned above. This paper also discusses the electronic control unit (ECU) developed jointly with Daihatsu that also meets these same requirements.

Fig.1 "Sonica" - A new mini-vehicle

Fig.2 Newly developed CVT unit

1.2 Design: Division of design roles between Daihatsu and Fujitsu Ten

During development of an ECU for electric transmission control (EAT/ECU) for the Storia vehicle, both Daihatsu and Fujitsu Ten put to use their own technologies and divided design roles for the sake of efficiency. This same division of design roles from the EAT/ECU development was applied in the case of the CVT/ECU design discussed in this paper. In order to derive maximum benefit from the division of design roles, Fujitsu Ten put to use their wealth of experience in integrated circuit (IC) technology to develop a new custom IC.

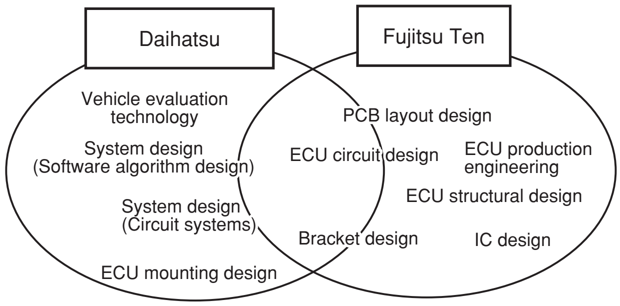


Fig.3 Sharing of design technology roles between Daihatsu and Fujitsu Ten

2 Outline of the Daihatsu CVT Unit

2.1 Differences with conventional CVT units (Characteristics)

The new CVT developed by Daihatsu features a compact structure utilizing a three-shaft system as opposed to the four-shaft one used in most conventional CVTs. The input power from the engine is reduced once by the planetary gear structure before it is transmitted to the CVT in order to reduce the operating speed of the CVT thereby improving transmission efficiency.

A conventional CVT consists of primary and secondary pulleys with a three-shaft differential gear making it necessary to provide a gear that reverses the rotation between the differential gear and CVT. However, the new CVT utilizes an additional planetary gear reduction structure on the front of the input shaft so that one of the rotation reversing gear shafts at the front of the differential gear was eliminated. This design allows for a reduction of components and thus provides a lightweight, compact CVT. This results in an CVT that actually has 6% less mass than CVTs for mini vehicle application produced by other companies.

Additionally, by using the planetary reduction gear structure to lower the speed by a factor of two-thirds, slippage of the belt from the pulley is reduced thereby improving transmission efficiency. Additionally, a reduction in the equivalent inertia of the engine shaft of the variable transmission unit together with the use of a small metal belt provides smooth acceleration performance.

As a result, fuel efficiency has been improved by approximately 15% in comparison to the four-speed A/T currently manufactured by Fujitsu Ten as well as a 10% improvement in acceleration performance to provide powerful yet smooth acceleration from low to high speeds which, as a result, provides mini vehicles with mobility performance comparable to compact vehicles.

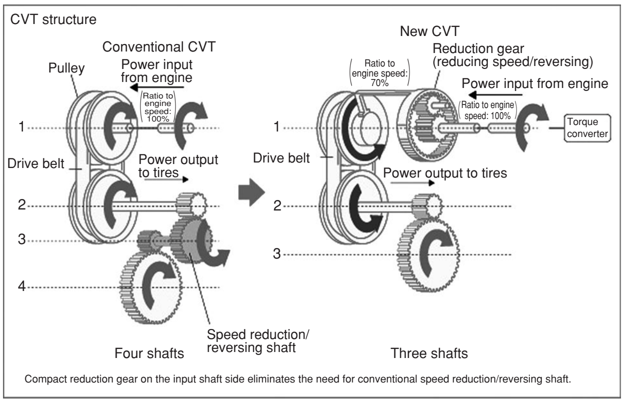
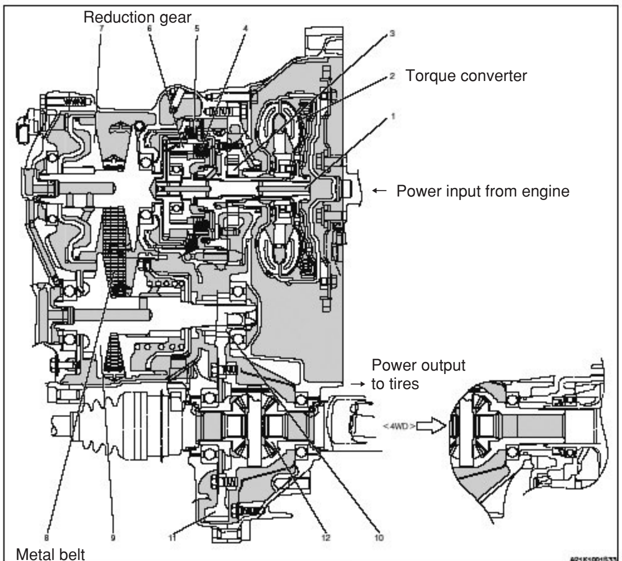


Fig.4 CVT reduction gear structure



1. Input shaft	7. Primary pulley
2. Torque converter	8. Metal belt
3. Oil pump	9. Secondary pulley
4. Reverse clutch	10. Differential drive gear
5. Forward brake	11. Differential ring gear
6. Planetary gear	12. Differential

Fig.5 CVT unit structure

3 Outline of the CVT/ECU

3.1 Outline of CVT/ECU control (Software control)

The CVT features a variable transmission control that constantly varies the gear ratios to control engine speed based on vehicle speed and accelerator opening angle at a speed that will yield optimal gas mileage. Variable transmission control utilizes solenoids to regulate the hydraulic pressure created by engine rotation as a means for variable transmission.

First, if the metal belt of the CVT is not strongly held by the pulley, then belt slippage occurs making belt retention and torque transmission impossible. Maximum hydraulic pressure in the unit can be utilized for belt tension but by using hydraulic pressure in proportion to only the engine speed, excessively high belt tension results thereby negatively affecting gas mileage. In order to avoid this problem, a linear solenoid for controlling belt tension is used for adjusting to the optimal pressure. Transmission torque is calculated based on the requested torque sent from a separate engine ECU via CAN communication and used to control the belt tension at an optimal amount.

Next, the variable transmission control constantly varies the pulley winding radius for optimal operation. The winding radius of the primary pulley (the pulley of the two that is on the engine side) is made larger than that of the secondary pulley (the pulley in opposition to the primary pulley, on the tire side) for low gear, and the reverse is done so that the winding radius of the primary pulley is made smaller for high gear. Creating a difference between the belt tension of the primary and secondary pulleys also creates a difference between the pulley winding radiuses. By increasing pressure on the primary pulley side, the pulley forces the belt to towards the outer periphery and the secondary pulley belt is pulled towards the inner periphery. Two solenoids are used to produce this pressure difference. One solenoid increases the pressure and the other one reduces the pressure.

Since solenoids perform an important control role within the CVT, the ECU performs essential malfunction detection. A critical issue is supplying this function for a low cost.

3.2 Outline of CVT/ECU hardware structure

The ECU consists of a 32-bit microcomputer for control calculation processing, a power supply circuit that converts 12-volt battery voltage to 5 volts and 2.5 volts for microcomputer-usage, an input converter circuit that converts ECU external sensor and SW signals for microcomputer processing, a CAN communication circuit for communication with the engine ECU and meters, an output circuit for driving external solenoids, and an EEPROM that stores previous correction values in order to stabilize variations occurring in the solenoid current sensing circuit within the ECU.

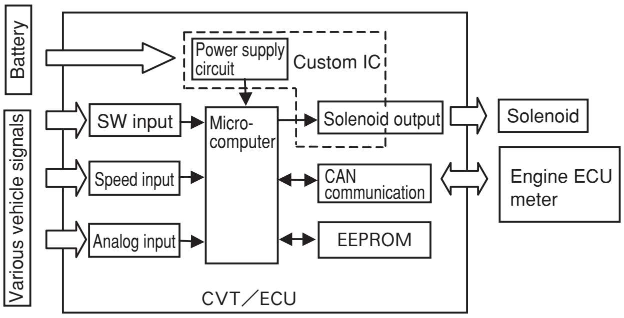


Fig.6 CVT/ECU hardware structure

In order to additionally reduce costs during the development of this ECU to below that of conventional design methods, a cost analysis of ECU components was performed where it was determined that the intelligent power device (IPD) used for driving solenoids for CVT control was the cause of the high cost. The IPD is equipped with a high performance power MOSFET that provides self-protection and failure detection functions, and has a multi-process configuration that makes the cost three to five times higher than that of single function power MOSFET. Additionally, while it is extremely rare, it has been discovered that there is a possible causal relation between the use of a single-chip IPD and functional impairment due to single-cause failures. For example, if two failures occur at the same time such as if there is an off failure when the solenoid load output drive is set to on and the failure detection does not function, then pressure of the secondary pulley performing belt tension control is released causing belt slippage and possibly resulting in belt deterioration or rupture. For this reason, an IPD with a general-use, low-cost power MOSFET was chosen to replace the conventional power MOSFET as a means to improve reliability together with providing a cost reduction. At the same time, power MOSFET protection and failure detection functions have been incorporated into a single-chip custom IC on the power supply circuit.

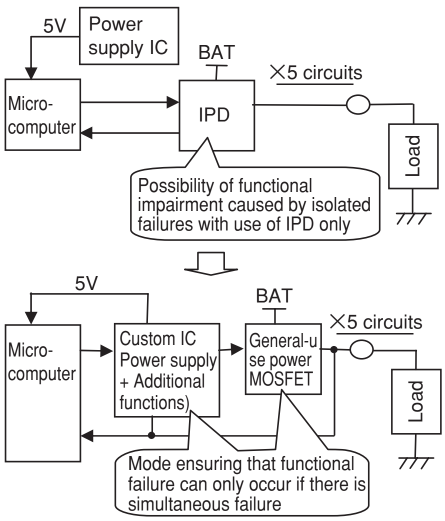


Fig.7 Diagnostic detection circuit structure

3.3 Development of the custom IC (Sprout)

Development of this ECU was initiated with only five months before preliminary test vehicle calibration, resulting in the challenge of having to complete development of the custom IC within four months time. Given the development scale for this project, it would normally require approximately a standard one-year schedule from specifications reviews until final completion of a custom IC. However, in order to complete the custom IC development in a short period, intellectual property related to circuitry and design assets of existing products were utilized, while specifications, circuitry and layout design processes were performed simultaneously. Additionally, an analog master slice was adopted as a means for custom IC development. This can be properly referred to as an analog version of a gate array as its design only consists of layers of aluminum wiring within the custom IC that are configured for performing circuit functions. Since IC manufacturing would start with the basic elements already configured, the manufacturing time could be shortened.

The analog master slice developed by Fujitsu Ten for on-board use (series name: ATOMIC 30) is characterized by its positioning of basic elements and also incorporates features that make it easy to design for on-board circuitry. For example, high-voltage resistant large-sized transistors that can be easily configured as an absorption circuit for vehicle negative surges or high current output stage are positioned around the pad, and small low-voltage resistant elements that can be configured for complicated functions are positioned in the interior circuit as a macro-unit (grouped elements).

Due to the element layout generally used for analog slices, the amount of elements that can be used are some 60 to 70% of the total, but with the ATOMIC 30, 90% of the total elements can be used.

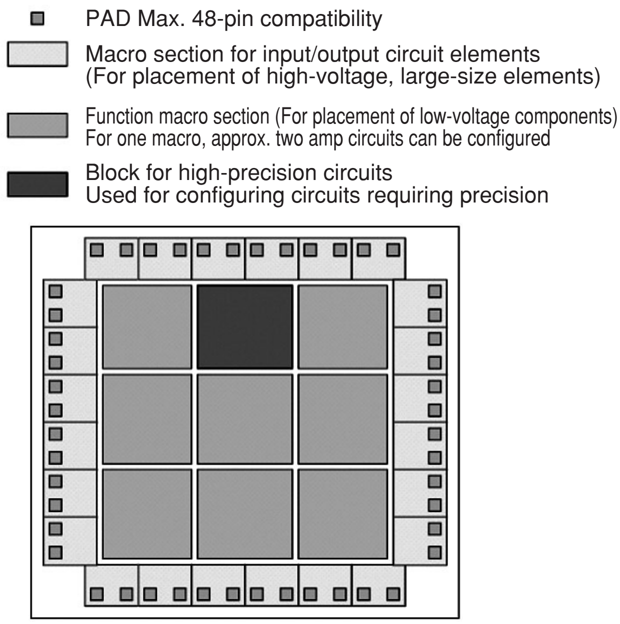


Fig.8 Atomic 30 elements layout

Package: L_QFP48
(7mm×7mm)
Frame: Cu
Manufacturer: Fujitsu Ten

Fig.9 IC external view

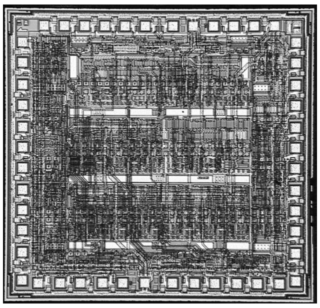


Fig.10 A picture of the developed chip

For the custom IC, the pre-driver circuit and the protection function of the power MOSFET are not only of single-chip construction but a dual-system regulator (5 V and 2.5 V) and microcomputer reset are integrated with the same single chip in order to increase added value.

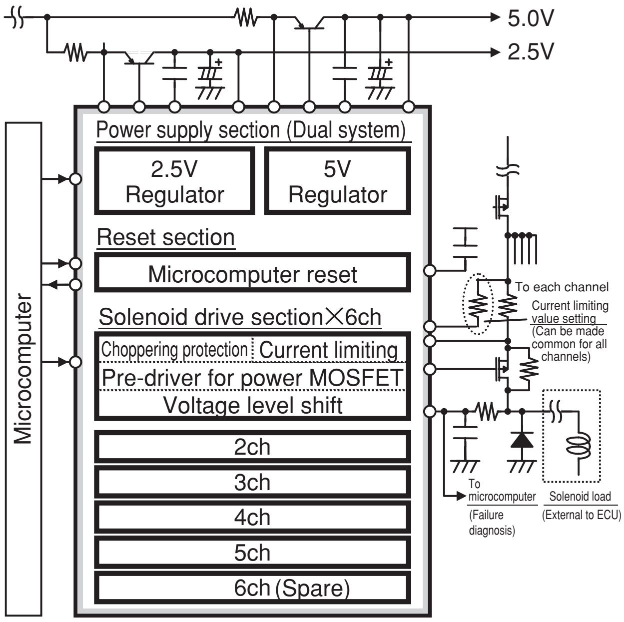


Fig.11 Custom IC function block diagram

The Power MOS FET must have the following protection functions for vehicle load ground faults or load half-short circuits(1).

①**Power MOSFET over-current detection protection function**

②**Power MOSFET overheating detection protection function**

As a countermeasure for ①, a power MOSFET over-current detection circuit and an external power MOSFET choppering protector are built into the custom IC to provide IPD-equivalent protection.

In relation to ②, since the temperature of power MOSFET itself cannot be directly detected by the custom IC, as the power MOSFET is a separate structure, other measures must be taken.

The reason that the IPD requires an over-heat protection function is because over-current protection alone will not prevent thermal damage to the IC. The IPD over-current detection level has a nearly ±50% tolerance due to the detection level being set by using element characteristics within the chip. An over-current detection level of ±50% tolerance means that when converted to heat and compared at the maximum, the tolerance is approximately 2.3 times the typical value. Furthermore, the tolerance of that value is according to the power MOSFET on-resistance and heat dissipation parameters so that if protection is based only on the over-current value then a temperature below that required to maintain power MOSFET integrity cannot be achieved.

In order to counter the above, this custom IC is configured such that the resistance established for the over-current level is in a position external to the custom IC as a measure that maintains the tolerance of the sensing level at ±10% (maximum value when converted to heat has a tolerance of approximately 1.2 times the typical value).

Due to this design, thermal damage to the power MOSFET will not occur even if the power MOSFET on-resistance and board heat parameters are subjected to the worst of overlapping conditions.

The configuration is such that the constant of one resistor external to the IC can be modified to simultaneously vary among multiple channels so that the over-current detection level can be adjusted to match the power MOSFET on-resistance or product heat diffusion requirements.

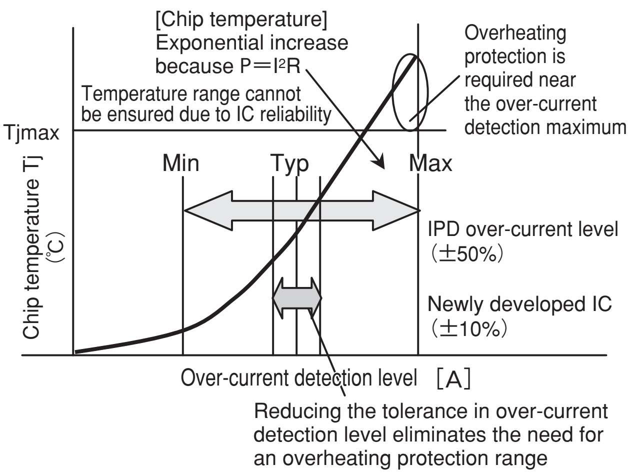


Fig.12 Protected area explanatory diagram

(1) Half-short circuit
Refers to short circuit failure mode that occurs when the load has impedance. This is different from a dead short circuit (full short circuit) in that the fault is difficult to detect since the short circuit current is small.

(2) Power MOSFET external choppering protection
This offers protection by lowering heat through the intermittent switching of the power MOSFET when over-current conditions are detected.

Since the power MOSFET pre-driver section of the custom IC represents a significant attribute of the component, the name "Sprout" was chosen as an acronym for "Super pre-output Driver".

Even though there was a short four-month development period, the features described above were successfully incorporated for the development of a custom IC equipped with the fail-safe functions required for on-board devices.

Fig. 13 shows the custom IC built into the concurrently developed CVT/ECU.

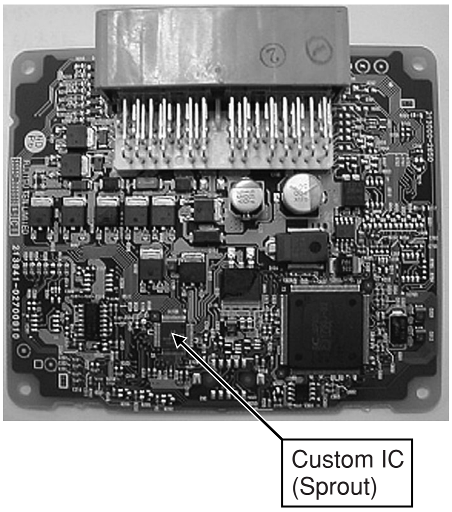


Fig.13 ECU circuit board

4 Conclusions

4.1 Development achievements

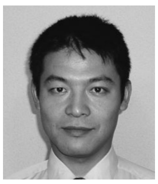
A significant achievement due to the development of this custom IC was that costs related to solenoid drive functions were reduced by 30% and the target cost of the ECU was achieved.

Additionally, in relation to IC specifications, the power MOSFET driver was given flexible specifications so that it can be used in the development of other products.

Design-related divisions at both Daihatsu and Fujitsu Ten collaborated from the ECU planning stage to produce an optimal configuration analysis and design review from a systems perspective, all of which led to an efficient and short development period and the successful incorporation of product quality.

Due to the above, both companies were able to complete the successful development of the CVT/ECU with additional merits achieved in the cost and product quality categories.

Profiles of Writers



Hiroyuki Hida

Entered DAIHATSU MOTOR CO., LTD. in 2000. Since then, engaged in the development and design of software for electronic control devices in automobiles. Currently in the Electronics Research & Development Department.

Yutaka Inui

Entered DAIHATSU MOTOR CO., LTD. in 1995. Since then, engaged in the development and design of hardware for electronic control devices in automobiles. Currently in the Electronics Research & Development Department.

Junichi Kusumoto

Entered the company in 1987. Since then, engaged in the development and design of electronic devices for automobiles. Currently in the Control Solution Department 1, AE Group.

Ryohei Kubota

Entered the company in 2001. Since then, engaged in the development and design of electronic devices for automobiles. Currently in the Control Solution Department 1, AE Group.

Yusuke Nishida

Entered the company in 2001. Since then, engaged in the development of analog LSI for automobiles. Currently in the Electron Device Research & Development Department of Research & Development Group.

Yosuke Taichi

Entered the company in 1983. Since then, engaged in the development and design of electronic devices for automobiles. Currently the Manager of the Control Solution Department 1, AE Group.