The Making of the Full Toroidal Variator

R. FUCHS T. TAMURA N. MCCULLOUGH K. MATSUMOTO

The full toroidal variator in its main application in an infinitely variable transmission demonstrated that it has reached the required technical maturity. Although successful implementations on various vehicles, from mowers to SUVs, the technology remains largely unknown to most of the engineering community. The recent market shift, from the automotive to the industrial and agricultural sector, further widens the range of applications and technical requirements.

This paper revisits the key features of the full toroidal variator. Starting with the basic geometrical concept, the actuation as well as the control of the variator and of the powertrain are then briefly reviewed pointing out the main mechanisms that permit to meet the requirements on fuel economy, enhanced maneuverability as well as other control objectives specific to each application.

***Key Words**: full toroidal variator, torque control, geared neutral, IVT, CVT*

1. Background

While the first toroidal drive was patented as early as 1877 by C.W Hunt[1)], it is only because of the significant improvement made during the past thirty years in the fields of materials, lubrication fluids, tribology and control, that this technology could reach the maturity required for a market breakthrough. Despite the remarkable progresses achieved in terms of fuel economy, durability and driveability, the full toroidal variator has still not made the expected breakthrough. Currently, the market, which best responded to the benefits offered by the full toroidal variator used in an IVT (Infinitely Variable Transmissions) arrangement, has shifted from the passenger car to the industrial/agricultural vehicle sector. The benefits recognized remain the significant fuel economy as well as the enhanced maneuverability (vehicle shuttling, low speed control, etc.) enabled by the geared neutral function. Others less known advantages are the control flexibility of the variator, the purely mechanical nature of this transmission, which allows full power operation over long period of time, low maintenance including oil "fill-for-life"[2)] and a relatively low cost compared to other modern and competitive technologies, such as hybrid electric vehicles.

As the full toroidal variator technology is taking momentum particularly on the Japanese market, it is timely to review the general concept and mechanism of the full toroidal variator. This paper recalls the basics of the full toroidal variator, starting for its geometry, its actuation and up to the powertrain control.

2. Geometry of the Full Toroidal Variator

Although relatively straightforward, the geometry of the full toroidal variator remains unclear to many. This section recalls the geometry of the full toroidal variator.

Figure 1 gives a step-by-step conceptual construction of the full toroidal variator. Let's first consider a toroidal volume as shown in **Fig. 1** (a). A sphere, having the same diameter as the cross section of the toroid, can be inserted into that volume (**Fig. 1** (b)). Mechanically, the toroidal volume is defined by using two discs with matching external surface (**Fig. 1** (c)). The name "full toroidal variator" comes from the fact that the matching surface of the discs covers an angle greater than 90°. In other words, this means that the discs hold the sphere into the cavity. The rollers, that transfer the power from one disc to the other while enabling the smooth variation of the speed ratio, are obtained by slicing the sphere (**Fig. 1** (d)). Not shown in **Fig. 1** is the crowning radius of the roller in the plane perpendicular to the previous slicing which enables adjusting the contact patch size. **Figure 1** (e) shows the two main components of the full toroidal variator: the disc and the roller. Finally, a single cavity of the full toroidal variator, as shown in **Fig. 1** (f), is typically composed of two discs and three rollers.

JTEKT has been active in developing these two key components for the past ten years. Based on its bearing core technology, JTEKT has developed a bearing steel the KUJ7 satisfying car makers requirements for durability under severe stress and high temperature conditions. For the production of these parts, standard processes of bearing like machining, heat and surface treatment are used, resulting in low manufacturing cost.

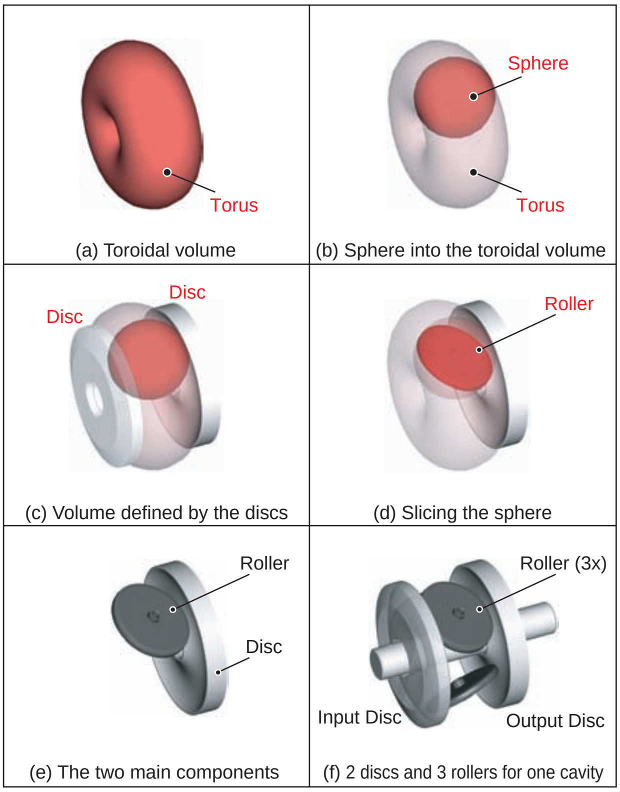

Fig. 1 Geometry of the full toroidal variator

3. Actuation of the Full Toroidal Variator

The actuation of the full toroidal variator is reviewed in this section and is based on the illustrations given in **Fig. 2**.

3. 1 The Endload

In toroidal variators, the power is transmitted at the contact between disc and roller by means of traction force. The contact conditions are met so as to have a hard EHL (elastohydrodynamic lubrication) regime. Under these conditions, low rate shearing of a thin film transmits substantial forces without permitting the metal parts to come in contact with each other[3]. The contact pressure required, typically of 1 to 4 GPa, is provided hydraulically by means of a clamping force or endload on the back one disc (**Fig. 2** (a)). By applying this endload, traction forces are generated at each contact. These forces are defined in a similar way as dry friction forces and with a traction coefficient depending, among others, on the contact slip. The losses occurring at the contact points are a major drawback, common to all friction type variators. More accurately, contact losses in toroidal variators can be split into two categories, spin and slip losses, affecting torque and speed respectively. Because of the geometry of the full toroidal variator, the spin losses are known to penalize the contact efficiency. This is partly compensated by the rollers being geometrically constrained within the cavity and therefore avoiding additional losses generated by thrust bearings. This is a major advantage as increasing the endload enables to transmit more power without mechanical limitation other than that related to contact stress. The three rollers arrangement also offers a stable and proper transfer of the axial effort from one disc to the other, alleviating fatigue constraint.

3. 2 The Reaction Force

In order to react the traction forces, each roller is mounted on a carriage connected to a hydraulic piston (**Fig. 2** (b)). This figure shows the complete mechanics of a single cavity of the full toroidal variator, which is characterized by a small number of parts. While the endload is the variator actuation required for transmitting power through contact points, the piston actuation fulfills the function of controlling the force transmitted. The traction forces generated at the contacts are controlled by actuation of the piston pressure. Because the product of the traction force F_t with the contact radial position $r_{i,o}$ on the disc defines the transmitted torques $T_{i,o}$, a direct relation between the piston pressure and the transmitted torques is obtained (**Fig. 2** (c)). One of the major benefits offered by this variator in terms of powertrain control is its ability to actuate the torque and therefore to know the load applied to the engine and the torque transmitted to the wheels. To the best of the author's knowledge, the full toroidal variator has the highest torque capacity of all CVTs due to its geometry (disc diameter and three rollers transmitting the power), which makes this technology versatile to vehicle platforms using engine ranging from 20 to over 300 kW of power. This comprises vehicles ranging from mower up to heavy truck including any type of passenger cars.

3. 3 The Castor Angle

From the principle of torque control, the major actuation mechanism enabling the speed ratio to shift remains to be revisited. **Figure 2** (d) highlights the castor angle. The roller carriages and pistons are oriented with this angle providing a self-alignment property to the rollers. This angle plays the same role as in a steering system. The rollers automatically track the speed ratio and no active control of the position is required. Therefore, the full toroidal variator does not rely on any active feedback control for its operation. This means that implementation of this variator in a powertrain requires no control other than the basic and common to all CVTs objective of managing the transfer of power from the engine to the wheel. This is a unique feature of the full toroidal variator.

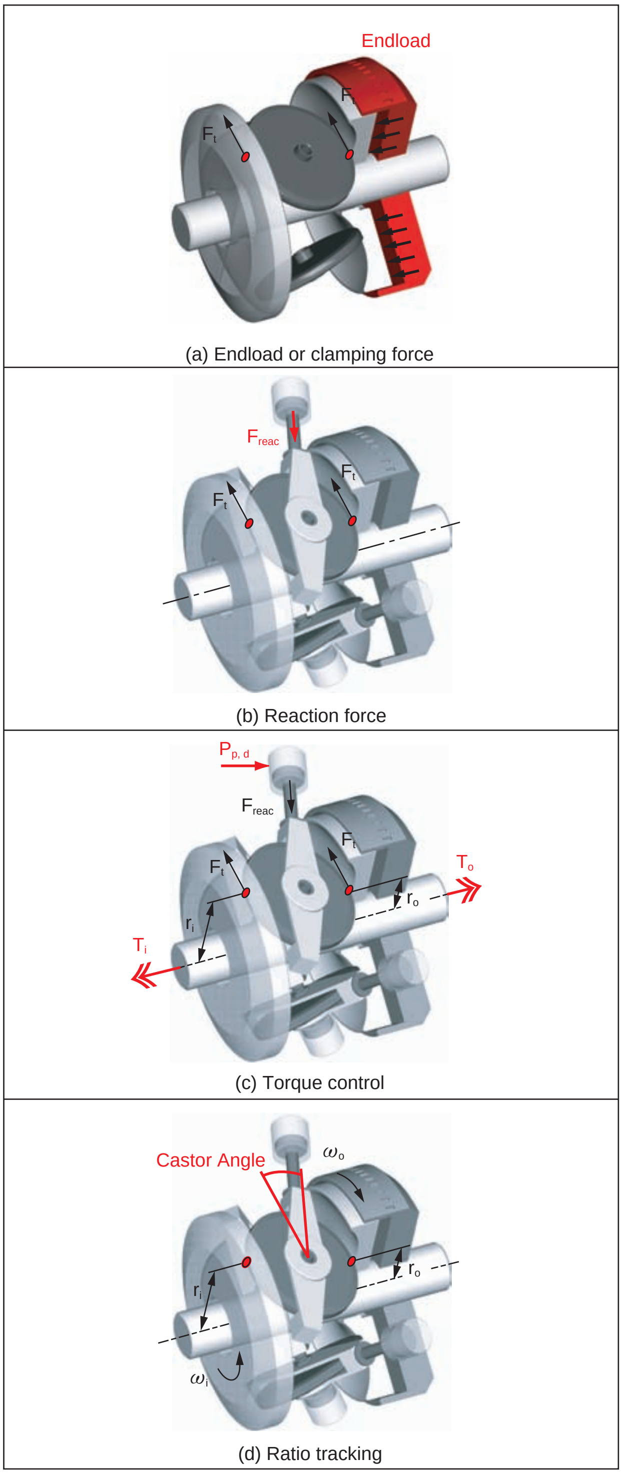

Fig. 2 Actuation of the full toroidal variator

3. 4 The Hydraulics

The hydraulics used to actuate the full toroidal variator is described based on **Fig. 3**.

Figure 3 (a) recalls the equilibrium condition on the roller between the traction force and the piston reaction force. Adding a carriage connected to a hydraulic piston, whose chambers are supposed closed, can be used to measure the torque transmitted at a fixed ratio. Indeed, torque transmitted can be calculated from the measured pressure of the chambers (**Fig. 3** (b)). Assuming that the speed ratio is constant, the torque can be actuated by using a simple pressure control circuit composed of pressure-reducing valve (**Fig. 3** (c)). These valves are accurate enough so as to enable the control of the pressure without any active feedback. As mentioned above, orienting the roller carriage with a castor angle enables geometrical tracking of the roller to match the speed ratio of the discs (**Fig. 3** (d)). The endload pressure is set from the maximum pressure set in the two chambers of the roller piston through a shuttle valve. This connection ensures a robust coupling between the contact normal force and the traction force avoiding gross slip to occur (**Fig. 3** (e)).

Other variators uses mechanical cam for the clamping. This mechanism offers also a robust matching of the endload force with respect of the transmitted torques but is not flexible. The cam design results from a trade off between all possible operating conditions of the variator overloading the contact and consequently penalizing the contact efficiency. For optimizing the clamping force, hydraulic endload were developed with active feedback control. Although such an approach is more flexible than the mechanical cam, its cost and complexity are major disadvantages.

Not shown in **Fig. 3** is the roller load equalization arrangement with all pistons connected in parallel. This configuration ensures optimal positioning of the rollers without relying on tight mechanical tolerances.

Hence, the hydraulics of the full toroidal variator takes advantage of the basic torque sensing property of toroidal variator resulting in low complexity and high reliability.

4. Example of a Variator Unit

Figure 4 shows an example of a variator unit for production. It is a dual cavity variator with the input and the output shaft in a coaxial arrangement. All pistons are located on a plane under the discs and connected through lever-type carriages to the rollers. This enables the hydraulic unit to be built using standard transmission techniques.

Visualizing a variator unit permits to sense the notion of variator system efficiency. Many have focused on the inherent contact efficiency related to the geometry only. This is over simplifying the characterization of the variator system efficiency, as it should include the roller carriage mechanism, the clamping actuation as well as the additional gears required to implement the variator into the transmission layout. Although the full toroidal variator in the configuration described offers many advantages over competitive technologies as mentioned above, a new structure is currently under development, which will further improve the current figures[4].

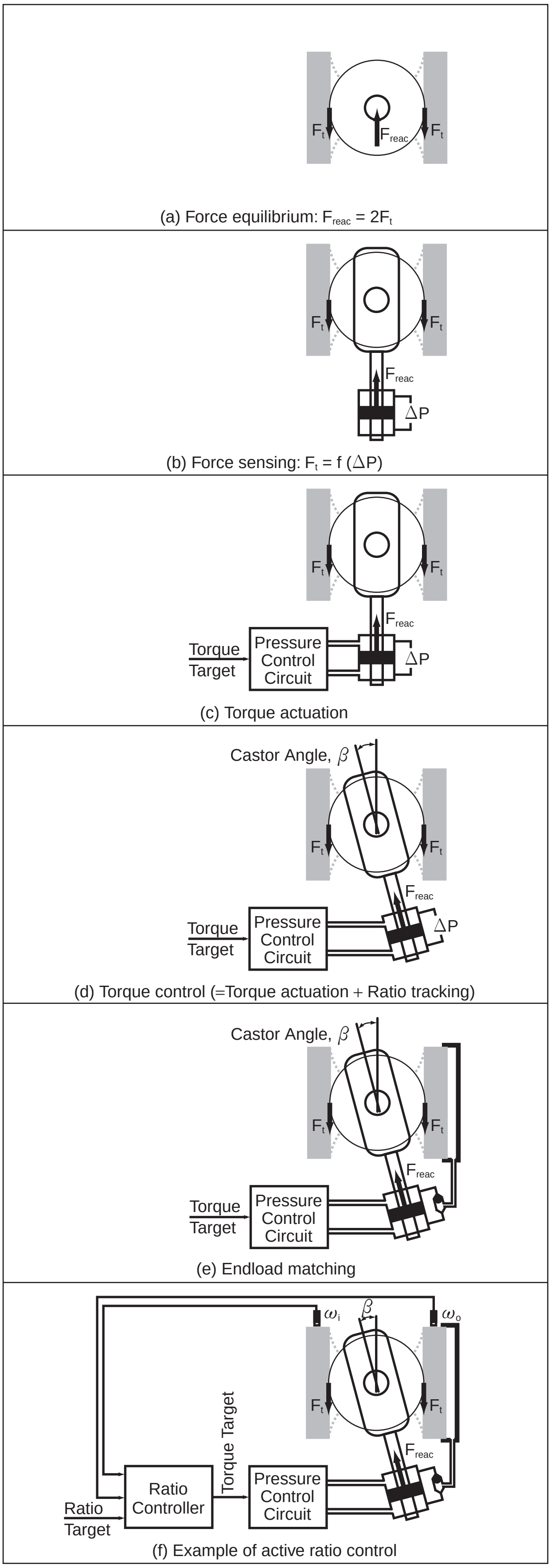

Fig. 3 Hydraulic actuation and variator control

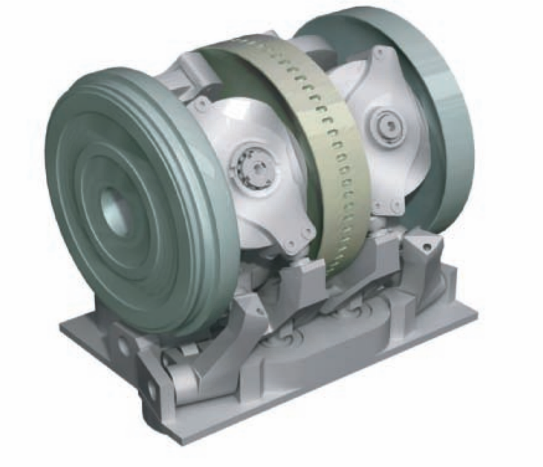

Fig. 4 Example of full a toroidal variator unit

5. Control of the Full Toroidal Variator

This section aims at describing the two control patterns possible with the full toroidal variator. These are the torque and ratio control.

Most variators are ratio controlled. This means that their actuation input has a direct relation with the speed ratio. Conversely, the speed ratio remains fixed independently of any external speed perturbation if the actuation input is constant. Ratio control relies always on the feedback of the measured speed ratio.

On the other hand, the full toroidal variator is torque controlled. As mentioned previously, this means that the actuation input has a direct relation with the transmitted torques. Consequently, the speed ratio shifts accordingly to any disc speed change even if the actuation input is constant. Torque control in the full toroidal variator does not rely on any feedback. It is an open-loop control[5].

Torque control offers particular benefits. First, an IVT (combination of a variator with an epicyclic gear train) can be operated at the geared neutral point without any active control. Because the rollers automatically track the speed ratio of the discs imposed by the condition of geared neutral, no additional control is necessary. If creep torque is required, the piston pressure can be increased accordingly. Second, the torques transmitted are accurately known. The consequence of the torque control is a high sensitivity of the speed ratio to external speed changes. Some applications may require the control of the speed ratio, in that case the torque-controlled full toroidal variator can easily be converted by adding a speed ratio feedback as shown in **Fig. 3** (f). Comparing **Fig. 3** (e) and (f) demonstrates the relative simplicity of the full toroidal variator in its basic configuration. The conversion from torque control to ratio control is easily achieved because of the slower response of the speed ratio relatively to the torque. The opposite is not true for variators, which are inherently ratio controlled, as the torque control realized from an active feedback is likely to results in low performance.

6. Control of Full Toroidal Variator Based-Powertrains

While the full toroidal variator has been presented as an open-loop torque actuator, its major advantage can be seen when considering the powertrain control. Because of its ability to accurately control the torque transmitted, the engine load and the wheel torque are known. This significantly facilitates the powertrain control strategy regardless of its objective. The control objective in automotive powertrains consists in relating the acceleration pedal to the vehicle power while controlling the engine speed for optimal efficiency. In industrial and agricultural vehicles, the control objective is to regulate the vehicle speed with or without optimizing the engine efficiency. Any of these objectives can be achieved with limited control complexity as the control plant can be easily linearized online and therefore having a minimum amount of controller gain, typically 2 to 4[6)]. This reduces the vehicle tuning time and the associated cost.

Figure 5 illustrates the basics of powertrain control when using a full toroidal variator. Euler described the dynamics of rotating inertia by stating that if the sum of the torque on that inertia is null $T_1 + T_2 = 0$, there is no acceleration $d\omega/dt = 0$ and the speed is constant $\omega = const$ (**Fig. 5** (a)). If the sum is different from zero $T_1 + T_2 \neq 0$, the inertia accelerates $d\omega/dt \neq 0$ (**Fig. 5** (b)). Controlling the speed of an inertia is a classical control problem. It can be achieved easily by using a motor. A motor is an electric actuator enabling the control of torque from a current input. The speed error of the inertia can be calculated by subtracting a speed command to the measured speed (feedback) and then fed it into a controller that will calculate the current input to command the motor (**Fig. 5** (c)). The speed control problem is solved in a similar way when using the full toroidal variator instead of the electrical motor. This variator is a hydro-mechanical actuator enabling the control of torque from a pressure input (electric current into a proportional solenoid valve). The controller calculates the pressure command of the variator from the speed error (**Fig. 5** (d)). The major difference between these two schemes is that the variator is not a power source. In the case of a powertrain, the considered inertia could be that of the vehicle and the power source would be the engine. **Figure 5** (e) shows an example of vehicle speed control common to industrial and agricultural applications. In that case, the engine would be equipped with a local controller such as a speed governor. **Figure 5** (f) shows the opposite configuration where the controlled inertia is that of the engine, typically to optimize its operating

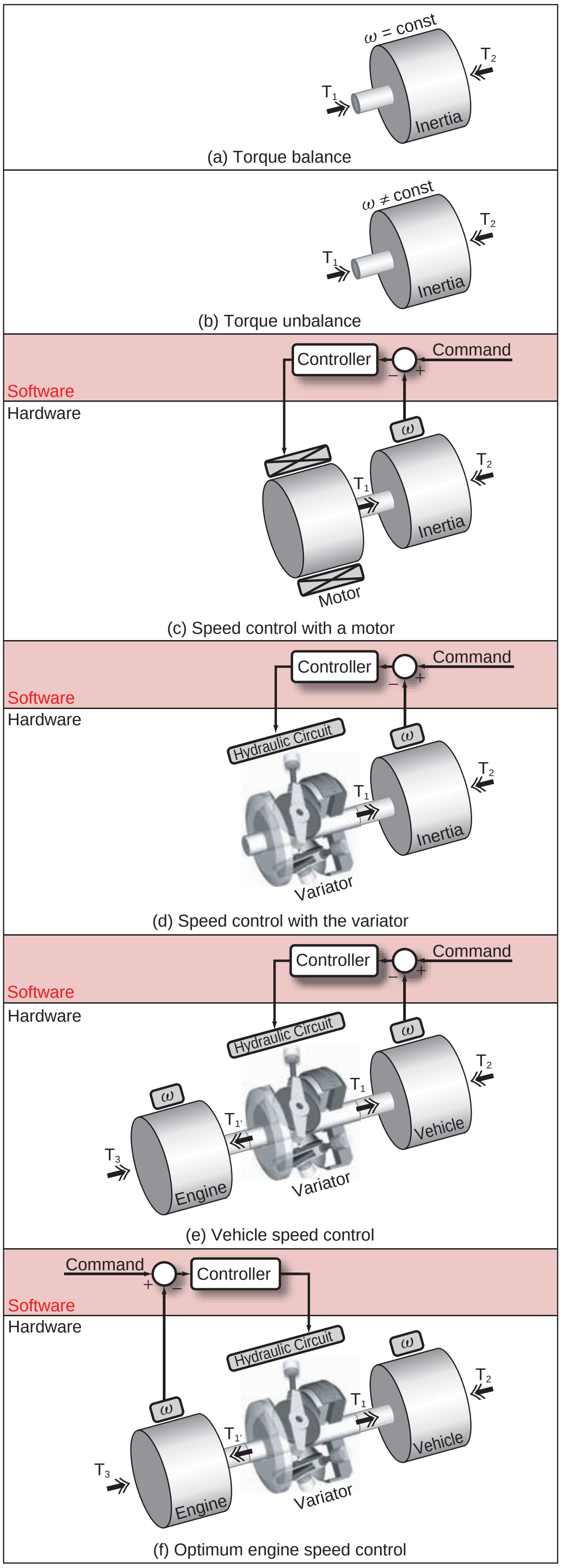

Fig. 5 Control of full toroidal variator based powertrains

point for best efficiency. In this case, the vehicle speed is not directly controlled. If vehicle performance is required, a vehicle speed controller can be cascaded to that of the engine because the two inertias respond with different time constant.

7. Summary

The full toroidal variator was revisited recalling the fundamental concepts behind its geometry, actuation and control. Although the benefits of this variator over competitive technologies are not easily seen at first glance, its proper design conception and the elegant mechanisms exploited results in a robust system with a low amount of parts and straightforward control requirements. The full toroidal variator offers high torque capacity and fast shifting response. It is a torque controlled drive requiring no feedback control. When used in an IVT, the geared neutral operation can be made without control, enabling smooth vehicle shuttling from forward to reverse and the opposite. Furthermore, low speed control is enabled for precise vehicle maneuver. These are some of the key features enabled by the full toroidal variator justifying the current recognition from industrial and agricultural vehicle companies. IVTs with two regimes are characterized by a wide ratio spread which permits the optimization of the engine efficiency in all operating conditions. This is the major drive for automotive makers for this technology. Last but not least, the various control objectives particular to each application platform can be met because of the unique control flexibility of the full toroidal variator.

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R. FUCHS*


T. TAMURA**


N. MCCULLOUGH**


K. MATSUMOTO**

* *Mechatronic Systems R&D Dept., Research & Development Center, Ph. D.*

** *Mechatronic Systems R&D Dept., Research & Development Center*