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(54) Title: METHOD FOR CONTROL OF A BALL PLANETARY TYPE CONTINUOUSLY VARIABLE TRANSMISSION IMPLEMENTING CONTACT PATCH TEMPERATURE MODEL OF TRACTION COMPONENTS

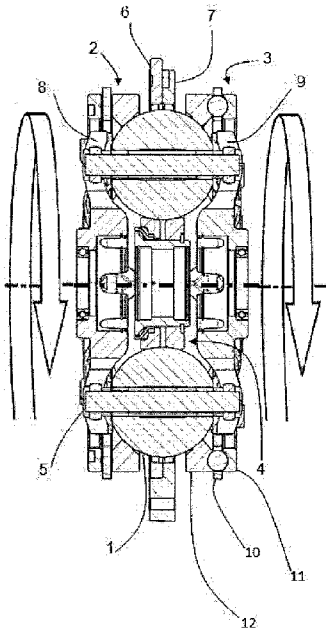


Figure 1

(57) Abstract: Provided herein is a system and method for controlling a multiple-mode continuously variable transmission having a ball planetary variator. The control system has a transmission control module configured to receive a plurality of electronic input signals, and to determine a mode of operation from a plurality of control ranges based at least in part on the plurality of electronic input signals. The transmission control module includes a CVP control module. The transmission control module or the CVP control module is configured to implement a software module programmed to determine a commanded CVP ratio based at least in part on an estimated contact patch temperature.

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METHOD FOR CONTROL OF A BALL PLANETARY TYPE CONTINUOUSLY VARIABLE TRANSMISSION IMPLEMENTING CONTACT PATCH TEMPERATURE MODEL OF TRACTION COMPONENTS

RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application No. 62/416,351 filed on November 2, 2016 which is incorporated herein by reference in its entirety.

BACKGROUND

Continuously variable transmissions (CVT) and transmissions that are substantially continuously variable are increasingly gaining acceptance in various applications. The process of controlling the ratio provided by the CVT is complicated by the continuously variable or minute gradations in ratio presented by the CVT. Furthermore, the range of ratios that are available to be implemented in a CVT are not sufficient for some applications. A transmission is capable of implementing a combination of a CVT with one or more additional CVT stages, one or more fixed ratio range splitters, or some combination thereof in order to extend the range of available ratios. The combination of a CVT with one or more additional stages further complicates the ratio control process, as the transmission will have multiple configurations that achieve the same final drive ratio. Different transmission configurations could, for example, multiply input torque across the different transmission stages in different manners to achieve the same final drive ratio. However, some configurations provide more flexibility or better efficiency than other configurations providing the same final drive ratio.

Slip of traction components in a continuously variable planetary (CVP)/CVT arrangement is in part a function of fluid μ which is itself directly correlated with temperature. Temperature measurement of rotating traction components is difficult and expensive to implement in a production.

A software model of traction component thermal dynamics run in real time can predict and avoid destructive slip and increase the system efficiency by reducing clamp load and/or fluid volumes to minimize system spin loss and hydraulic pump loads

based on confidence that thermal model is accurately predicting slip avoidance bands. Thus, there is a need for an improved and low cost method of control based on temperature that can provide the advantages discussed above.

SUMMARY

Provided herein is a method for controlling a continuously variable transmission having a ball-planetary variator (CVP), the CVP having a first traction ring and a second traction ring each in contact with a plurality of balls, wherein the first traction ring contacts each ball at a first contact patch, and the second traction ring contacts each balls at a second contact patch. The method includes the steps of estimating a first contact patch temperature of the first contact patch; estimating a second contact patch temperature of the second contact patch; and commanding a CVP ratio based at least in part on the first contact patch temperature and the second contact patch temperature.

INCORPORATION BY REFERENCE

All publications, patents, and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication, patent, or patent application was specifically and individually indicated to be incorporated by reference.

BRIEF DESCRIPTION OF THE DRAWINGS

Novel features of the preferred embodiments are set forth with particularity in the appended claims. A better understanding of the features and advantages of the present embodiments will be obtained by reference to the following detailed description that sets forth illustrative embodiments, in which the principles of the preferred embodiments are utilized, and the accompanying drawings of which:

Figure 1 is a side sectional view of a ball-type variator.

Figure 2 is a plan view of a carrier member that used in the variator of Figure 1.

Figure 3 is an illustrative view of different tilt positions of the ball-type variator of Figure 1.

Figure 4 is a block diagram schematic of a transmission control system that could be implemented in a vehicle.

Figure 5 is a block diagram schematic of a software module implemented in the transmission control system of Figure 4 having a model based estimator for contact patch temperature.

Figure 6 is a block diagram schematic of another software module implemented in the transmission control system of Figure 4 having an analytical estimator for contact patch temperature.

Figure 7 is a block diagram schematic of yet another software module implemented in the transmission control system of Figure 4 having a contact patch temperature estimator.

Figure 8 is a block diagram schematic of an analytical estimator for contact patch temperature that is implementable in the transmission control system of Figure 4.

Figure 9 is a block diagram of a contact patch delta temp module that is implemented in the analytical estimator of Figure 8.

Figure 10 is a block diagram of a rolling entrainment velocity module that is implemented in the analytical estimator of Figure 8.

Figure 11 is a block diagram of a calculated ratio and droop module that is implemented in the analytical estimator of Figure 8.

Figure 12 is a block diagram of a ball surface velocity module that is implemented in the analytical estimator of Figure 8.

Figure 13 is a block diagram of a ring surface velocity module that is implemented in the analytical estimator of Figure 8.

Figure 14 is a block diagram of an entrainment velocity module that is implemented in the analytical estimator of Figure 8.

Figure 15 is a block diagram of a specific power loss module that is implemented in the analytical estimator of Figure 8.

Figure 16 is a schematic diagram depicted a thermal model of heat losses in a contact patch of the CVP.

Figure 17 is a block diagram of a contact patch temperature estimator that is implemented in the software modules of Figure 5 or Figure 7.

Figure 18 is a block diagram of the contact patch temperature estimator of Figure 17.

Figure 19 is a block diagram of a multiple dimension transfer function coefficient look-up process.

Figure 20 is a block diagram of a thermal limit control module that is implemented in the software modules of Figures 5-7.

Figure 21 is a block diagram of a contact patch temperature module that is implemented in the software module of Figure 7.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

It is to be understood that the preferred embodiments may assume various alternative orientations and step sequences, except where expressly specified to the contrary. It is also to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification are simply exemplary embodiments of the concepts defined herein. Hence, specific dimensions, directions or other physical characteristics relating to the embodiments disclosed are not to be considered as limiting, unless expressly stated otherwise.

Provided herein is a computer-implemented method and system for controlling a variable ratio transmission of a vehicle having an engine coupled to the variable transmission having a ball-planetary variator (CVP), the vehicle having a plurality of sensors and an electronic controller.

An electronic controller is described herein that enables electronic control over a variable ratio transmission having a continuously variable ratio portion, such as a Continuously Variable Transmission (CVT), Infinitely Variable Transmission (IVT), or variator. In some embodiments, the electronic controller is configured to receive input signals indicative of parameters associated with the engine coupled to the transmission. The parameters can include, but are not limited to, throttle position sensor values, accelerator pedal position sensor values, vehicle speed, gear selector position, user-selectable mode configurations, and the like, or some combination thereof. The electronic controller receives one or more control inputs. The electronic controller determines an active range and an active variator mode based on the input signals and control inputs. The electronic controller controls a final drive ratio of the variable ratio transmission by controlling one or more electronic actuators and/or solenoids that control the ratios of one or more portions of the variable ratio transmission.

The electronic controller described herein is described in the context of a continuous variable transmission, such as the continuous variable transmission of the type described in U.S. Patent Application Number 14/425,842, entitled "3-Mode Front Wheel Drive And Rear Wheel Drive Continuously Variable Planetary Transmission" and, PCT Patent Application Number PCT/US16/030930, entitled "Control Method of Synchronous Shifting of a Multi-Range Transmission Including a Continuously Variable Planetary Mechanism", each assigned to the assignee of the present application and hereby incorporated by reference herein in its entirety. However, the electronic controller is not limited to controlling a particular type of transmission but rather, is optionally configured to control any of several types of variable ratio transmissions.

Provided herein are configurations of CVTs based on a ball type variator, also known as CVP, for continuously variable planetary. Basic concepts of a ball type Continuously Variable Transmissions are described in United States Patent No. 8,469,856 and 8,870,711 incorporated herein by reference in their entirety. Such a CVT, adapted herein as described throughout this specification, includes a number of balls (planets, spheres) 1, depending on the application, two ring (disc) assemblies with a conical surface contact with the balls, as input (first) traction ring assembly 2 and output (second) traction ring assembly 3, and an idler (sun) assembly 4 as shown on FIG. 1. In some embodiments, the idler assembly 4 includes a first idler ring and a second idler ring, each in contact with each ball at a radially inward location with respect to the first traction ring assembly and the second traction ring assembly. In other embodiments, the idler assembly 4 includes a single idler ring in contact with each ball at a radially inward location with respect to the first traction ring assembly and the second traction ring assembly. In some embodiments, the output traction ring assembly 3 includes an axial force generator mechanism. The balls are mounted on tiltable axles 5, themselves held in a carrier (stator, cage) assembly having a first carrier member 6 operably coupled to a second carrier member 7. The first carrier member 6 rotates with respect to the second carrier member 7, and vice versa. In some embodiments, the first carrier member 6 is substantially fixed from rotation while the second carrier member 7 is configured to rotate with respect to the first carrier member, and vice versa. In one embodiment, the first carrier member 6 is provided with a

number of radial guide slots 8. The second carrier member 7 is provided with a number of radially offset guide slots 9, as illustrated in FIG. 2. The radial guide slots 8 and the radially offset guide slots 9 are adapted to guide the tiltable axles 5. The axles 5 are adjustable to achieve a desired ratio of input speed to output speed during operation of the CVT. In some embodiments, adjustment of the axles 5 involves control of the position of the first and second carrier members to impart a tilting of the axles 5 and thereby adjusts the ratio of the variator. Other types of ball CVTs also exist, like the one produced by Milner, but are slightly different.

The working principle of such a CVP of FIG. 1 is shown on FIG. 3. The CVP itself works with a traction fluid. The lubricant between the ball and the conical rings acts as a solid at high pressure, transferring the power from the input ring, through the balls, to the output ring. By tilting the balls' axes, the ratio is changed between input and output. When the axis is horizontal, the ratio is one, as illustrated in FIG. 3, when the axis is tilted, the distance between the axis and the contact point change, modifying the overall ratio. All the balls' axes are tilted at the same time with a mechanism included in the carrier and/or idler. Embodiments disclosed herein are related to the control of a variator and/or a CVT using generally spherical planets each having a tiltable axis of rotation that is adjustable to achieve a desired ratio of input speed to output speed during operation. In some embodiments, adjustment of said axis of rotation involves angular misalignment of the planet axis in a first plane in order to achieve an angular adjustment of the planet axis in a second plane that is substantially perpendicular to the first plane, thereby adjusting the ratio of the variator. The angular misalignment in the first plane is referred to here as “skew”, “skew angle”, and/or “skew condition”. In one embodiment, a control system coordinates the use of a skew angle to generate forces between certain contacting components in the variator that will tilt the planet axis of rotation. The tilting of the planet axis of rotation adjusts the ratio of the variator.

As used here, the terms “operationally connected,” “operationally coupled”, “operationally linked”, “operably connected”, “operably coupled”, “operably coupleable”, “operably linked,” and like terms, refer to a relationship (mechanical, linkage, coupling, etc.) between elements whereby operation of one element results in a corresponding, following, or simultaneous operation or actuation of a second element.

It is noted that in using said terms to describe the embodiments, specific structures or mechanisms that link or couple the elements are typically described. However, unless otherwise specifically stated, when one of said terms is used, the term indicates that the actual linkage or coupling will take a variety of forms, which in certain instances will be readily apparent to a person of ordinary skill in the relevant technology.

For description purposes, the term "radial", as used herein indicates a direction or position that is perpendicular relative to a longitudinal axis of a transmission or variator. The term "axial" as used herein refers to a direction or position along an axis that is parallel to a main or longitudinal axis of a transmission or variator.

It should be noted that reference herein to "traction" does not exclude applications where the dominant or exclusive mode of power transfer is through "friction." Without attempting to establish a categorical difference between traction and friction drives herein, generally, these are understood as different regimes of power transfer. Traction drives usually involve the transfer of power between two elements by shear forces in a thin fluid layer trapped between the elements. The fluids used in these applications usually exhibit traction coefficients greater than conventional mineral oils. The traction coefficient (μ) represents the maximum available traction forces that would be available at the interfaces of the contacting components and is a measure of the maximum available drive torque. Typically, friction drives generally relate to transferring power between two elements by frictional forces between the elements. For the purposes of this disclosure, it should be understood that the CVTs described here could operate in both tractive and frictional applications. As a general matter, the traction coefficient μ is a function of the traction fluid properties, the normal force at the contact area, and the velocity of the traction fluid in the contact area, among other things. For a given traction fluid, the traction coefficient μ increases with increasing relative velocities of components, until the traction coefficient μ reaches a maximum capacity after which the traction coefficient μ decays. The condition of exceeding the maximum capacity of the traction fluid is often referred to as "gross slip condition". Traction fluid is also influenced by entrainment speed of the fluid and temperature at the contact patch, for example, the traction coefficient is generally highest near zero speed and decays as a weak function of speed. The traction

coefficient often improves with increasing temperature until a point at which the traction coefficient rapidly degrades.

As used herein, "creep", "ratio droop", or "slip" is the discrete local motion of a body relative to another and is exemplified by the relative velocities of rolling contact components such as the mechanism described herein. In traction drives, the transfer of power from a driving element to a driven element via a traction interface requires creep. Usually, creep in the direction of power transfer, is referred to as "creep in the rolling direction." Sometimes the driving and driven elements experience creep in a direction orthogonal to the power transfer direction, in such a case this component of creep is referred to as "transverse creep."

For description purposes, the terms "prime mover", "engine," and like terms, are used herein to indicate a power source. Said power source could be fueled by energy sources including hydrocarbon, electrical, biomass, solar, geothermal, hydraulic, and/or pneumatic, to name but a few. Although typically described in a vehicle or automotive application, one skilled in the art will recognize the broader applications for this technology and the use of alternative power sources for driving a transmission including this technology.

Those of skill will recognize that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the embodiments disclosed herein, including with reference to the transmission control system described herein, for example, could be implemented as electronic hardware, software stored on a computer readable medium and executable by a processor, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans could implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present embodiments. For example, various illustrative logical blocks, modules, and circuits described in connection with the embodiments disclosed herein could be implemented or performed with a general purpose processor, a digital signal processor (DSP), an application

specific integrated circuit (ASIC), a field programmable gate array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general-purpose processor could be a microprocessor, but in the alternative, the processor could be any conventional processor, controller, microcontroller, or state machine. A processor could also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. Software associated with such modules could reside in RAM memory, flash memory, ROM memory, EPROM memory, EEPROM memory, registers, a hard disk, a removable disk, a CD-ROM, or any other suitable form of storage medium known in the art. An exemplary storage medium is coupled to the processor such the processor reads information from, and write information to, the storage medium. In the alternative, the storage medium could be integral to the processor. The processor and the storage medium could reside in an ASIC. For example, in one embodiment, a controller for use of control of the CVT includes a processor (not shown).

In some embodiments, the control system described herein includes a digital processing device, or use of the same. In further embodiments, the digital processing device includes one or more hardware central processing units (CPU) that carry out the device's functions. In still further embodiments, the digital processing device further includes an operating system configured to perform executable instructions. In some embodiments, the digital processing device is optionally connected a computer network. In further embodiments, the digital processing device is optionally connected to the Internet such that it accesses the World Wide Web. In still further embodiments, the digital processing device is optionally connected to a cloud computing infrastructure. In other embodiments, the digital processing device is optionally connected to an intranet. In other embodiments, the digital processing device is optionally connected to a data storage device.

In accordance with the description herein, suitable digital processing devices include, by way of non-limiting examples, server computers, desktop computers, laptop computers, notebook computers, sub-notebook computers, netbook computers, netpad

computers, set-top computers, media streaming devices, handheld computers, Internet appliances, mobile smartphones, tablet computers, personal digital assistants, and vehicles. Those of skill in the art will recognize that many smartphones are suitable for use in the system described herein. Suitable tablet computers include those with booklet, slate, and convertible configurations, known to those of skill in the art.

In some embodiments, the digital processing device includes an operating system configured to perform executable instructions. The operating system is, for example, software, including programs and data, which manages the device's hardware and provides services for execution of applications. Those of skill in the art will recognize that suitable server operating systems include, by way of non -limiting examples, FreeBSD, OpenBSD, NetBSD®, Linux, Apple® Mac OS X Server®, Oracle® Solaris®, Windows Server®, and Novell® NetWare®. Those of skill in the art will recognize that suitable personal computer operating systems include, by way of non-limiting examples, Microsoft® Windows®, Apple® Mac OS X®, UNIX®, and UNIX-like operating systems such as GNU/Linux®. In some embodiments, the operating system is provided by cloud computing. Those of skill in the art will also recognize that suitable mobile smart phone operating systems include, by way of non-limiting examples, Nokia® Symbian® OS, Apple® iOS®, Research In Motion® BlackBerry OS®, Google® Android®, Microsoft® Windows Phone® OS, Microsoft® Windows Mobile® OS, Linux®, and Palm® WebOS®.

In some embodiments, the device includes a storage and/or memory device. The storage and/or memory device is one or more physical apparatuses used to store data or programs on a temporary or permanent basis. In some embodiments, the device is volatile memory and requires power to maintain stored information. In some embodiments, the device is non-volatile memory and retains stored information when the digital processing device is not powered. In further embodiments, the non-volatile memory includes flash memory. In some embodiments, the nonvolatile memory includes dynamic random-access memory (DRAM). In some embodiments, the non-volatile memory includes ferroelectric random access memory (FRAM). In some embodiments, the non-volatile memory includes phase-change random access memory (PRAM). In other embodiments, the device is a storage device including, by way of non-limiting examples, CD-ROMs, DVDs, flash memory devices, magnetic disk

drives, magnetic tapes drives, optical disk drives, and cloud computing based storage. In further embodiments, the storage and/or memory device is a combination of devices such as those disclosed herein.

In some embodiments, the control system disclosed herein includes at least one computer program, or use of the same. A computer program includes a sequence of instructions, executable in the digital processing device's CPU, written to perform a specified task. Computer readable instructions may be implemented as program modules, such as functions, objects, Application Programming Interfaces (APIs), data structures, and the like, that perform particular tasks or implement particular abstract data types. In light of the disclosure provided herein, those of skill in the art will recognize that a computer program may be written in various versions of various languages.

The functionality of the computer readable instructions may be combined or distributed as desired in various environments. In some embodiments, a computer program includes one sequence of instructions. In some embodiments, a computer program includes a plurality of sequences of instructions. In some embodiments, a computer program is provided from one location. In other embodiments, a computer program is provided from a plurality of locations. In various embodiments, a computer program includes one or more software modules. In various embodiments, a computer program includes, in part or in whole, one or more web applications, one or more mobile applications, one or more standalone applications, one or more web browser plug-ins, extensions, add-ins, or add-ons, or combinations thereof.

Referring now to FIG. 4, in one embodiment, a transmission controller 100 includes an input signal processing module 102, a transmission control module 104 and an output signal processing module 106. The input signal processing module 102 is configured to receive a number of electronic signals from sensors provided on the vehicle and/or transmission. The sensors optionally include temperature sensors, speed sensors, position sensors, among others. In some embodiments, the signal processing module 102 optionally includes various sub-modules to perform routines such as signal acquisition, signal arbitration, or other known methods for signal processing. The output signal processing module 106 is optionally configured to electronically communicate to a variety of actuators and sensors. In some embodiments, the output

signal processing module 106 is configured to transmit commanded signals to actuators based on target values determined in the transmission control module 104. The transmission control module 104 optionally includes a variety of sub-modules or sub-routines for controlling continuously variable transmissions of the type discussed here. For example, the transmission control module 104 optionally includes a clutch control sub-module 108 that is programmed to execute control over clutches or similar devices within the transmission. In some embodiments, the clutch control sub-module 108 implements state machine control for the coordination of engagement of clutches or similar devices. The transmission control module 104 optionally includes a CVP control sub-module 110 programmed to execute a variety of measurements and determine target operating conditions of the CVP, for example, of the ball-type continuously variable transmissions discussed here. It should be noted that the CVP control sub-module 110 optionally incorporates a number of sub-modules for performing measurements and control of the CVP. One sub-module included in the CVP control sub-module 110 is described herein.

Referring now to FIG. 5, in some embodiment, the transmission control module 104 is configured to implement a software module 150. In some embodiments, the software module 150 is provided with a model-based estimator 151 configured to provide an estimate for a temperature at the contacting location of the ball and traction rings, for example. The estimated temperature is sometimes referred to herein as "contact patch temperature", "contact temperature", or "patch temperature". In some embodiments, the model-based estimator 151 is configured to include a number of empirical models of contact patch temperature based on operating condition of the CVP. For example, the model-based estimator 151 is optionally created by collecting through measurement a data set of contact patch temperatures during operation of the CVP. In some embodiments, the contact patch temperature determined by the model-based estimator 151 is passed to a thermal limit control module 152. The thermal limit control module 152 determines a number of commanded control limits that are passed to a commanded output module 153 for corresponding actuator commands. In some embodiments, the thermal limit control module 152 is provided with an engine torque limit module 154 configured to determine a limit to engine torque based at least in part on the estimated contact patch temperature. The thermal limit control module 152

includes a CVP ratio control module 155 that determines a limit to CVP ratio based at least in part on the estimated contact patch temperature. In some embodiments, the CVP ratio control module 155 includes algorithms to enable ratio dither based at least in part on the estimated contact patch temperature. For example, a ratio dither control scheme similar to those disclosed in U.S. Patent Applications 62/287,309 and 62/368,290, each of which are hereby incorporated by reference, are implemented in the CVP ratio control module 155. In some embodiments, the thermal limit control module 152 includes an over temperature diagnostics module 156 configured to determine a fault status based at least in part on the estimated contact patch temperature.

Referring now to FIG. 6, in some embodiment, the transmission control module 104 is configured to implement a software module 160. In some embodiments, the software module 160 is provided with an analytical estimator 161 configured to provide an estimate for a temperature at the contacting location of the ball and traction rings, for example. The estimated temperature is sometimes referred to herein as "contact patch temperature", "contact temperature", or "patch temperature". In some embodiments, the analytical estimator 161 is configured to determine an estimated contact patch temperature with a number calculations based on physical relationships between operating conditions of the CVP. In some embodiments, the contact patch temperature determined by the analytical estimator 161 is passed to a thermal limit control module 162. The thermal limit control module 162 determines a number of commanded control limits that are passed to a commanded output module 163 for corresponding actuator commands. In some embodiments, the thermal limit control module 162 is provided with an engine torque limit module 164 configured to determine a limit to engine torque based at least in part on the estimated contact patch temperature. The thermal limit control module 162 includes a CVP ratio control module 165 that determines a limit to CVP ratio based at least in part on the estimated contact patch temperature. In some embodiments, the CVP ratio control module 165 includes algorithms to enable ratio dither based at least in part on the estimated contact patch temperature. In some embodiments, the thermal limit control module 162 includes an over temperature diagnostics module 166 configured to determine a fault status based at least in part on the estimated contact patch temperature.

Referring now to FIG. 7, in some embodiments, the transmission control module 104 is configured to implement a software module 170. In some embodiments, the software module 170 is provided with a contact patch temperature module 171 configured to provide an estimate for a temperature at the contacting location of the ball and traction rings, for example. In some embodiments, the contact patch temperature module 171 includes a model-based estimator 172 and an analytical estimator 173. The contact patch temperature module 171 is configured to determine an estimated contact patch temperature based on a combined estimate from the model-based estimator 172 and the analytical estimator 173. In some embodiments, the contact patch temperature determined by the contact patch temperature module 171 is passed to a thermal limit control module 174. The thermal limit control module 174 determines a number of commanded control limits that are passed to a commanded output module 178 for corresponding actuator commands. In some embodiments, the thermal limit control module 174 is provided with an engine torque limit module 175 configured to determine a limit to engine torque based at least in part on the estimated contact patch temperature. The thermal limit control module 174 includes a CVP ratio control module 176 that determines a limit to CVP ratio based at least in part on the estimated contact patch temperature. In some embodiments, the CVP ratio control module 176 includes algorithms to enable ratio dither based at least in part on the estimated contact patch temperature. In some embodiments, the thermal limit control module 174 includes an over temperature diagnostics module 177 configured to determine a fault status based at least in part on the estimated contact patch temperature.

Provided herein are embodiments of control methods implementing an analytical estimator that determines the flash temperature at the contact patch. Flash temperature is the temperature rise induced by friction in the contact patch. Frictional heating sources in the contact patch include x-direction slip, y-direction side slip, and a spin induced moment in the z-direction. A simplification technique can be employed by calculating the non-dimensional Peclet number to determine if a one dimensional z-direction only heat transfer analysis is appropriate. The Peclet number (L) is a relation between material heat transfer properties and the relative speed of the moving heat source through the contact patch. For velocities in the contact patch above approximately 0.5 m/s, CVP rolling contact easily satisfies the required conditions for

one dimensional simplification (L > 10). The Ertz equation below defines the flash temperature primarily in terms of maximum stress and slip velocity in the x-direction and assumes that the resulting heat transfer is in the z-direction only from one body to the other. This requires explicit modeling of contact patch parameters to implement and has circular dependency on the flash temperature. Additionally, this requires correlating modeling efforts with a measured true contact patch temperature to validate the thermal model that feeds into the traction coefficient model used to generate the components of the contact patch loss model:

$$\Theta_{max} = 1.253 \frac{\varepsilon_A \mu v_s p_0}{B_A} \sqrt{\frac{a}{v_A}}$$

where Θ_{max} = flash temperature rise (K), ε_A = heat flow partition factor (function of material properties, assume 0.5 if identical materials), B_A = thermal effusivity ($Ws^{0.5}/Km^2$), μ = coefficient of traction, p_0 = peak contact patch stress (Pa), v_s = slip velocity in the rolling direction (m/s), a = contact patch radius in the rolling direction (m), and v_A = rolling entrainment velocity (m/s).

Ertz further defines the frictional power dissipation rate in the contact patch as:

$$q_{dot} = \frac{\pi}{4} \varepsilon_A \mu v_s p_0$$

where q_{dot} equals the frictional power dissipation rate in the contact patch (W/m^2).

By combining the Ertz equation for flash temperature and a frictional power dissipation rate, an expression of flash temperature in terms of heat dissipation rate in the contact patch is developed:

$$\Theta_{max} = 1.595 \frac{q_{dot}}{B_A} \sqrt{\frac{a}{v_A}}$$

where q_{dot} equals the frictional power dissipation rate in contact patch (W/m^2).

The heat rate is formed from the sum of slip, side slip, and spin which can be modeled from traction patch data and contains a circular dependency on traction coefficient vs. temperature. To avoid the circular dependency, in some embodiments, a CVP efficiency loss model to determine the heat dissipation rate from CVP efficiency data only. The heat dissipation rate in the contact patch is the net result of the combined effects of slip, side slip, and spin. Therefore, in some embodiments, a model

of the contact patch temperature rise using the experimentally generated CVP efficiency maps as the primary input is used.

In some embodiments, the heat partition factor ε_A is assumed to be 0.5 with equal heat flow into the planet and the ring based on the ring and planet having identical material properties. However, the heat partition factor may vary. CVP loss is distributed across the first traction ring ("ring 1") and the second traction ring ("ring 2") traction interface linearly in proportion to the ring torque values. In some embodiments, from a given operating condition, the input torque, the input speed, and the CVP ratio values are used to calculate the necessary intermediate parameters including: the first traction ring torque is optionally determined from a torque converter model provided in the transmission controller 100; the second traction ring torque for given operating mode is based at least in part on the first traction ring torque and the CVP ratio; rolling entrainment velocity (m/s), which is described in more detail in reference to FIG. 8 below; contact patch area (m^2) for the first traction ring and the second traction ring (the sun contact is optionally included); the first traction ring and second traction ring frictional losses (W) from CVP efficiency tables and previously stated assumptions; heat removal (W) from lubrication in the contact patch; the first traction ring and second traction ring specific power losses (W/m^2) from loss and traction patch area; and flash temperature (K) (modified Ertz equation). In some embodiments the contact patch area (m^2) for the first traction ring and the second traction ring is calculated using a look up table for major and minor radii and then area from π*a*b is implemented. In some embodiments, major and minor radii are determined with online mathematical calculations.

Referring now to FIG. 8, in some embodiments, an analytical estimator 180 is implementable for the analytical estimator 161 or the analytical estimator 173. The analytical estimator 180 is a software module that includes a system off cooling dynamics model 181, a contact patch delta temperature module 182, a final contact patch temperature module 183, and a CVP lubrication system flow model 184. The analytical estimator 180 receives a number of input signals from the transmission controller 104 including, but not limited to, signals indicative of a key-off timer 185, a wake up signal 186, an oil sump temperature 187, an ambient temperature 188, a final contact temperature 189, an input torque 191, an input speed 192, a current state 193,

and a commanded CVP ratio 194, among others. In some embodiments, the final contact temperature 189 is a stored parameter indicative of the last recorded contact temperature during previous key-on operation of the CVP. In some embodiments, the system off cooling dynamics module 181 is configured to determine an initial contact temperature 190 that is passed to the final contact patch temperature module 183. In some embodiments, the key-off timer 185 and the wake up signal 186 are standard functions of most commercial transmission control systems, vehicle control systems, or engine control systems. The oil sump temperature 187 is optionally provided by a typical temperature sensor located in the transmission oil sump. The current state 193 is a indicative a transmission mode of operation, typically of varying speed ranges multiple mode operation. The input torque 191 is a signal based on engine operating condition. The input speed 192 is a signal from a speed sensor configured to sense the input speed to the CVP.

In some embodiments, the contact patch delta temperature module 182 is configured to determine a number of parameters that characterize the contact patch between the ball and each traction ring. These parameters include a radius 199 (or "b1 input") of the contact patch for the first traction ring; a radius 201 of the contact patch for the second traction ring ("b2 input") a change in contact patch temperature 197 for the first traction ring ("first traction ring contact patch heating delta temp"); a change in contact patch temperature 203 for the second traction ring ("second traction ring contact patch heating delta temp"); a contact patch area 198 for the first traction ring ("first traction ring contact patch area"); a contact patch area 202 for the second traction ring ("second traction ring contact patch area"); an entrainment velocity 200 for fluid in the contact patch of the first traction ring ("first traction ring entrainment velocity"); an entrainment velocity 204 for fluid in the contact patch of the second traction ring ("second traction ring entrainment velocity"); and an actual CVP ratio 205. The contact patch delta temperature module 182 passes the first traction ring contact patch heating delta temp 197 signal and the second traction ring contact patch heating delta temp 203 signal to the final contact patch temperature module 183. The final contact patch temperature module 183 determines a first traction ring contact patch temperature 206 and a second traction ring contact patch temperature 207. In some embodiments, the first traction ring contact patch temperature 206 and the second traction ring contact

patch temperature 207 are passed to the CVP lubrication system flow model 184, among other parameters, to determine a first traction ring contact cooling loss 195 and a second traction ring contact cooling loss 196. In some embodiments, the CVP lubrication system flow model 184 is an empirically derived look-up table based. The first traction ring contact cooling loss 195 and the second traction ring contact cooling loss 196 are passed to the contact patch delta temp module 182.

Still referring to FIG. 8, system off cooling dynamics model 181 is optionally implemented in the analytical estimator 180 to include variations due to differing thermal properties of bearing steel and working fluids such as traction fluid, lubrication fluid, and other oils fluids used in the transmission. Each of the above components may show a different thermal cooling curve in response to ambient soak conditions. Typical vehicle control modules use existing logic to monitor key-off timers for on-board diagnostic (OBD) purposes. Therefore, a correlation between the cooling curve to specific key-off times and ambient temperature conditions is determined through the use of calibration tables. Initial contact patch temperature after long key-off should be equal to transmission sump temperature. For shorter key-off times, a look up table calculates a calibrated cooling ratio from 1 - 0 utilizing measured cooling curve data, with 1 representing no key-off cooling time and 0 representing maximum key-off cooling time needed for system components to soak to equal temperatures (potentially several hours). Therefore, the initial contact patch temperature is defined as follows:

$$\Theta_{initial} = T_{oil} + Ratio * (\Theta_{final} - T_{oil})$$

Still referring to FIG. 8, in some embodiments the CVP lubrication system flow model 184 accounts for the cooling of the balls in the contact patch from flow of traction fluid and from convection cooling outside the contact patch. An equation provided below, calculates the heat removal (q) from the contact patch due only to the traction fluid that passes over the contact patch. The mass flow rate of the fluid is derived from the entrainment velocity, contact patch width, film thickness determined from look up tables containing theoretical values or from online mathematical calculations, and the fluid density.

$$q = m_{dot} * C_p * \Delta T$$

The heat removed is then subtracted from the frictional heat loss found from the CVP efficiency tables and used to calculate the specific power loss and associated

contact temperature rise. In some embodiments, calculations for heat removal optionally include convective heat transfer effects within the CVP as well as other heat transfer effects imparted on the system from fluid flow on CVP components.

Final contact temperature is the sum of the flash temperature and the current oil temperature.

$$\Theta_{final} = \Theta_{max} + T_{oil}$$

Referring now to FIG. 9, in some embodiments, the contact patch delta temperature module 182 includes a rolling entrainment velocity module 210, a contact patch geometry module 211, a specific power loss module 212, and a traction ring contact patch delta temperature module 215. In some embodiments, the specific power loss module 212 is optionally configured to have a first traction ring specific loss module and a second traction ring specific loss module based on the first traction ring contact cooling loss 195 and the second traction ring contact cooling loss 196, among other parameters. In some embodiments, the contact patch geometry module 211 implements well-known calculations to determine size and shape parameters for each contact patch location. For example, the contact patch geometry module 211 determines the first traction ring contact patch area 198, the b1 input 199, the b2 input 201, and the second traction ring contact patch area 202, among others. In some embodiments, the traction ring contact patch delta temperature module 215 is optionally configured to a first traction ring contact patch delta temperature module and a second traction ring contact patch delta temperature module. For clarity and conciseness, where applicable, calculations for the contact patch between the first traction ring and the ball are the same as calculations for the contact patch between the second traction ring and the ball. Referring still to FIG. 9, in some embodiments, the traction ring contact patch delta temperature module 215 is configured to implement a calculation for the change of temperature of the contact patch in the first traction ring or the second traction ring contact patch using the previously described modified Ertz equation:

$$\Delta T = 1.595 \frac{q_{dot}}{B_A} \sqrt{\frac{a}{v_A}}$$

Referring now to FIG. 10, in some embodiments, the rolling entrainment velocity module 210 includes a calculated ratio and droop module 220, a ball surface velocity module 221, a ring surface velocity module 222, and an entrainment velocity module 223. The rolling entrainment velocity module 210 receives a number of input signals including, but not limited to, speed sensors configured to sense speed of the traction ring assemblies, and executes algorithms and calculations to determine a first traction ring entrainment velocity 200 and a second traction ring entrainment velocity 204.

Referring now to FIG. 11, in some embodiments, the calculated ratio and droop module 220 receives a first traction ring speed 192A, a second traction ring speed 192B from other modules in the transmission controller 104. The second traction ring speed 192B is divided by the first traction ring speed 192A at a divider block 230 to provide an actual CVP ratio 205. The commanded CVP ratio 194 is subtracted from the actual CVP ratio 205 at a subtraction block 231. The product of the subtraction block 231 is divided again by the commanded CVP ratio 194 at a divider block 232 to form a CVP droop 224.

Turning now to FIG. 12, in some embodiments, the ball surface velocity module 221 is configured to receive the CVP droop 224, the commanded CVP ratio 194, and a first ring surface velocity 225 and a second ring surface velocity 226. The ball surface velocity module 221 includes a droop model look-up table 240 configured to provide a loss fraction based at least in part on the commanded CVP ratio 194. In some embodiments, the loss fraction is also based on the assumption that droop is distributed between the first traction ring and the second traction ring in proportion to the torque at each traction ring. The loss fraction determined in the droop model look-up table 240 is passed to a subtraction block 241 that passes a product to a multiplier 242. The multiplier 242 multiplies the first ring surface velocity 225 by the CVP droop 224 and the loss fraction determined by the droop model look-up table 240. A multiplier 243 multiplies the loss fraction by the CVP droop 224, the second ring surface velocity 226, and a constant, for example (-1). In some embodiments, for a given direction of torque applied to the CVP, the constant is a value of positive one (+1) to indicate that the first traction ring is going faster than the ball at the first contact patch, and a constant of negative one (-1) is used to indicate that the second traction ring is going slower than

the ball at the second contact patch. The product of the multiplier 242 is added to the first ring surface velocity 225 at a summation block 244 to form a first planet surface velocity 227. The product of the multiplier 243 is added to the second ring surface velocity 226 at a summation block 245 to form a second planet surface velocity 228.

Passing now to FIG. 13, in some embodiments, the ring surface velocity module 222 multiples the first traction ring speed 192A by a constant at a multiplier 235. For illustrative example, the constant value is 2*pi*(traction ring radius)*0.001. The product of the multiplier 235 is divided by 60 at the divider 236 to form the first traction ring surface speed 225. In some embodiments, the ring surface velocity module 222 multiples the second traction ring speed 192B by a constant at a multiplier 237. For illustrative example, the constant value is 2*pi*(traction ring radius)*0.001. The product of the multiplier 237 is divided by 60 at the divider 238 to form the second traction ring surface speed 226.

Referring now to FIG. 14, in some embodiments, the entrainment velocity module 223 sums the first traction ring surface speed 225 and the first planet surface velocity 227 at the summation block 250. The product of the summation block 250 is divided by 2 at a divider 251 to form the first traction ring entrainment velocity 200. In some embodiments, the entrainment velocity module 223 sums the second traction ring surface speed 226 and the second planet surface velocity 228 at the summation block 252. The product of the summation block 252 is divided by 2 at a divider 253 to form the second traction ring entrainment velocity 204.

Turning now to FIG. 15, and referring still to FIG. 9, in some embodiments, the specific power loss module 212 includes a droop model look-up table 260 configured to provide a loss fraction based at least in part on the commanded CVP ratio 194. The loss fraction determined by the droop module look-up table 260 is subtracted from 1 at a subtraction block 261 to form a first traction ring loss fraction 262. The specific power loss module 212 includes a CVP efficiency look-up table 263 configured to provide a CVP efficiency based at least in part on the commanded CVP ratio 194, a first traction ring torque 191A, and the first traction ring speed 192A. The CVP efficiency determined by the CVP efficiency look-up table 263 is subtracted from 1 at a subtraction block 264. The result of the subtraction block 264 is passed to a loss modifier gain 265. The loss modifier gain 265 is optionally set as a constant value of

0.5. For example, for components having nearly identical material properties, half of the loss is attributed to the ball and the other half of the loss is attributed to the traction ring. In some embodiments, the first traction ring loss fraction 262 is multiplied by a first traction ring power 268 at a multiplier 269. The result of the multiplier 269 is passed to a multiplier 267 where the result of the multiplier 269 is multiplied by the result of the loss modifier gain 265. A subtraction block 270 subtracts the first traction ring contact cooling loss 195 from the result of the multiplier 267. The result of the subtraction block 270 is divided at a divider 271 by the product of the first traction ring contact patch area 198 and a gain 272 to form a first traction ring specific power loss 213. The gain 272 is indicative of the number of balls provided in the CVP. It should be appreciated that the specific power loss module 212 is depicted for calculating the specific power loss for the first traction ring. Calculations for specific power loss in the second traction ring are implemented in a substantially similar manner. In some embodiments, the result determined by the droop module look-up table 260 is representative of the specific power loss fraction of the second traction ring.

Turning now to FIGS. 16-19, embodiments of a model-based estimator that is optionally implemented as the model-based estimator 151 or the model-based estimator 172 will be described. Referring specifically to FIG. 16, a thermal model 300 is used to illustrate the thermal resistance between a CVP lube temperature 301 and a contact patch temperature 302. In some embodiments, the thermal model 300 is a transfer function to determine the contact patch temperature from heat losses. For example, the thermal model 300 is a partial fraction network, such as a Foster model, configured to use estimated heat losses as the input parameters and produce a contact temperature as the output. The R-values represent thermal resistance values which determine the final contact temperature. Thermal resistance is a heat property and the measurement by which an object or material resists heat transfer. The Tau values represent the time constant of the thermal resistance, and is characteristic of the transient behavior and time taken to reach the final contact temperature.

Solution accuracy of the thermal model 300 is dependent on the number of ordered pairs of (R_i, Tau_i) used to generate the transfer function, the number of ordered pairs selected by a designer of the system is a trade-off between solution accuracy and the computational bandwidth. The ordered pairs do not represent discrete physical

components of the system. For example, a first order solution is capable of converging on a correct final value for a steady state temperature rise, however the rise time and decay time of any transient conditions will be absent from the estimation. For this example a fourth order transfer function is selected to balance solution accuracy with computational expense. The representative transfer function is given below where N_i represents the tunable numerator coefficients and D_i represents the tunable denominator coefficients.

$$T_{contact}(t) = \frac{N_3 s^3 + N_2 s^2 + N_1 s + N_0}{D_4 s^4 + D_3 s^3 + D_2 s^2 + D_1 s + D_0}$$

As used herein the "contact patch" is understood to refer to each of the four interfaces between the ball and the first traction ring, the second traction ring, the first traction sun, and the second traction sun, as is illustrated in FIG. 1. Therefore, the full estimation model will contain four transfer functions each representing an individual contact region in the transmission. Estimated final contact patch temperature is composed of the initial CVP lube flow temperature added to the output of the transfer function. CVP lube flow temperature can be either the measured sump oil temperature or alternatively composed of the initial sump temperature plus a modeled temperature rise induced by pump pressure work as well as conduction and/or convection effects within the lube flow circuit.

Referring now to FIGS. 17 and 18, in some embodiments, a contact patch temperature estimator 305 is configured to be used as a model-based estimator such as the model-based estimator 151 or the model-based estimator 172. The contact patch temperature estimator 305 receives a number of input signals from the transmission controller 104 such as a first traction ring contact patch loss 306, a second traction ring contact patch loss 307, a CVP lube flow temperature 308, a first traction sun contact patch loss 309, and a second traction sun contact patch loss 310. The contact patch temperature estimator 305 determines a first traction ring temperature 311, a second traction ring temperature 312, a first traction sun temperature 313, and a second traction sun temperature 314. In some embodiments, the contact patch temperature estimator 305 includes a first traction ring transfer function 315, a first traction sun transfer function 316, a second traction ring transfer function 317, and a second traction sun transfer function 318. The CVP lube flow temperature 308 is added to the result of the

first traction ring transfer function 315, the first traction sun transfer function 316, the second traction ring transfer function 317, and the second traction sun transfer function 318 to form the first traction ring temperature 311, the second traction ring temperature 312, the first traction sun temperature 313, and the second traction sun temperature 314, respectively. In some embodiments, the given input set used to log the measured temperature output is fed into an offline process to reduce the real-time computational burden. The off-line process is optionally configured as a software tool such as a Simulink based model that accepts data recorded during operation. The off-line process optionally includes the model-based estimator 151 or the model-based estimator 172, for example. The off-line process uses a parameter estimation function to iteratively tune the calibration coefficients, such as the R values and the Tau values of the thermal model 300, until the model output converges on the known correct solution based on the recorded vehicle data. The calibration coefficients are then updated in the thermal model 300, for example, and applied during operation of the vehicle at the next key-on.

Referring now to FIG. 19, in some embodiments, the coefficients used in the first traction ring transfer function 315, the first traction sun transfer function 316, the second traction ring transfer function 317 are optionally configured to implement multiple dimension look-up tables. A multiple dimension transfer function coefficient look-up process 320 includes a multiple dimension look-up table 323 that is configured to receive the CVP lube flow temperature 308, a modeled CVP lube flow rate 321, and a rolling entrainment velocity 322 to form a solution set of transfer function coefficients 324. In order to account for additional operating conditions that would affect the heat transfer model, the transfer function coefficients would be taken from a look up table with additional dimensions to account for variation in lube flow, variations in lube temperature, entrainment velocity, each of which alters the thermal dynamics of the system. In some embodiments, calibration values are created that represent thermal resistance and thermal capacitance of the overall system. Thermal resistance quantifies steady state ultimate temperature achieved while thermal capacitance quantifies dynamic time to ultimate temperature achieved. The given input set used to log the measured temperature output is fed into an offline process to reduce the real-time computational burden. The off-line process is optionally configured as a

software tool such as a Simulink based model that accepts data recorded during operation. The off-line process optionally includes the model-based estimator 151 or the model-based estimator 172, for example. The off-line process uses a parameter estimation function iteratively tune the calibration coefficients, such as the R values and the Tau values of the thermal model 300, until the model output converges on the known correct solution based on the recorded vehicle data. The calibration coefficients are then updated in the thermal model 300, for example, and applied during operation of the vehicle at the next key-on.

Passing now to FIG. 20, and still referring to FIGS. 5-7, in some embodiments, the thermal limit control module 152, the thermal limit control module 162, and the thermal limit control module 174 are configured to provide a variety of control and diagnostic functions in the transmission controller 104. In some embodiments, the thermal limit control module 174 receives an estimated contact temperature set 325. The estimated contact temperature set 325 includes estimates for temperature at the contacting location between traction components in the CVP. The methods to determine the estimated contact temperatures have been described herein, for example, in reference to the analytical estimator 180, the analytical estimator 161 or the analytical estimator 173. The largest estimated contact patch temperature among the values in the estimated contact temperature set 325 is determined at a comparison block 326. The maximum value is passed to an engine torque limit function 327, a short term ratio dither function 328, an over temperature diagnostic function 329, and a CVP ratio command limit function 330. The collective command signal set 331 is passed to other modules of the transmission controller 104 for actuation, such as the CVP control module 110.

Referring now to FIG. 21, and still referring to FIG. 7, in some embodiments, the contact patch temperature module 171 is configured to receive an analytical temperature estimation 340 and a parametric modeled temperature estimation 341, each formed by methods described herein. The contact patch temperature module 171 is configured to receive a signal indicative of a CVP input power 342 and a CVP input speed rate of change 343 from other modules in the transmission controller 104. In some embodiments, the contact patch temperature module 171 includes a weighting coefficients look-up table 244 that provides a gain based at least in part on the

operating condition of the CVP characterized by the CVP input power 342 and the CVP input speed rate of change 343. The gain determined by the weighting coefficients look-up table 344 is subtracted from 1 at a subtraction block 345. A multiplier 346 multiples the result of the subtraction block 345 by the analytical temperature estimation 340. A multiplier 347 multiplies the result of the subtraction block 345 by the parametric temperature estimation 341. The results of the multiplier 346 and the multiplier 347 are summed at a summation block 348 to determine a final temperature estimation 349. Careful consideration of the current operating conditions combined with appropriate weighting functions produce an optimal temperature solution in regards to the inherent strengths and weaknesses of each method. The analytical flash temperature method is ideally suited to the high power, high transient case and is less suited for the steady state condition as the un-modeled bulk planet temperature changes. Alternatively, while the model-based estimation method automatically compensates for the bulk planet temperature change, it is likely less able to track high power or fast transients. Therefore, the optimal weighting strategy places more emphasis on the parameter estimation method at lower loads and give higher emphasis towards the analytical flash temperature method under higher loading conditions.

Provided herein is a computer-implemented control system for a continuously variable transmission having a ball-planetary variator (CVP), the CVP having a first traction ring and a second traction ring each in contact with a plurality of balls, wherein the first traction ring contacts each ball at a first contact patch, and the second traction ring contacts each balls at a second contact patch, the computer-implemented control system including: a digital processing device including an operating system configured to perform executable instructions and a memory device; a computer program including instructions executable by the digital processing device, the computer program including a software module configured to monitor and control the CVP; wherein the software module estimates a first contact patch temperature of the first contact patch, wherein the software module estimates a second contact patch temperature of the second contact patch, and wherein the software module commands a CVP ratio based at least in part on the first contact patch temperature and the second contact patch temperature.

In some embodiments, the software module commands an engine torque limit based at least in part on the first contact patch temperature and the second contact patch temperature. In some embodiments, the first contact patch temperature and the second contact patch temperature are determined by a model-based estimator. In some embodiments, the first contact patch temperature and the second contact patch temperature are determined by an analytical estimator. In some embodiments, the first contact patch temperature and the second contact patch temperature are determined by a contact patch temperature module having a model-based estimator and an analytical estimator. In some embodiments, the analytical estimator includes a system off cooling dynamics model configured to provide an initial contact patch temperature based at least in part on an oil sump temperature and an ambient temperature. In some embodiments, the analytical estimator includes a contact patch delta temperature module. In some embodiments, the contact patch delta temperature module further includes a rolling entrainment velocity module configured to determine an entrainment velocity at each contact patch based at least in part on an input speed and a commanded CVP ratio, a contact patch geometry module configured to provide a plurality of parameters indicative of size and shape of each contact patch based at least in part on an input torque to the CVP, a specific power loss module configured to determine a specific power loss for each contact patch based at least in part on the plurality of parameters indicative of size and shape and the CVP ratio, and a traction ring contact patch delta temperature module configured to determine a change in a contact patch temperature for each traction ring based at least in part on the specific power loss for each contact patch.

In some embodiments, the analytical estimator includes a CVP lubrication system flow model. In some embodiments, the analytical estimator further includes a final contact patch temperature module configured to determine the first contact patch temperature and the second contact patch temperature based at least in part on the change in contact patch temperature for each traction ring determined by the traction ring contact patch delta temperature module. In some embodiments, the rolling entrainment velocity module is configured to calculate an actual CVP ratio and a CVP droop. In some embodiments, the entrainment velocity at each contact patch is based at least in part on the CVP droop. In some embodiments, the model-based estimator

further includes a first traction ring transfer function configured to determine the first contact patch temperature based at least in part on a heat loss at the first contact patch, and a second traction ring transfer function configured to determine the second contact patch temperature based at least in part on a heat loss at the second contact patch. In some embodiments, the model-based estimator further includes a first traction sun transfer function and a second traction sun transfer function. In some embodiments, the first traction sun transfer function is configured to determine a first traction sun contact temperature based at least in part on a heat loss at a contact patch between a first traction sun and the balls. In some embodiments, the second traction sun transfer function is configured to determine a second traction sun contact temperature based at least in part on a heat loss at a contact patch between a second traction sun and the balls. In some embodiments, the first traction ring transfer function, the first traction sun transfer function, the second traction ring transfer function, and the second traction sun transfer function receive a plurality of transfer function coefficients from a multiple dimension look-up table. In some embodiments, the contact patch temperature module further includes a weighting coefficients look-up table configured to provide a weighting coefficient based at least in part on an input speed and an input torque of the CVP.

It should be noted that the description above has provided dimensions for certain components or subassemblies. The mentioned dimensions, or ranges of dimensions, are provided in order to comply as best as possible with certain legal requirements, such as best mode. However, the scope of the preferred embodiments described herein are to be determined solely by the language of the claims, and consequently, none of the mentioned dimensions is to be considered limiting on the preferrred embodiments, except in so far as any one claim makes a specified dimension, or range of thereof, a feature of the claim.

The foregoing description details certain embodiments. It will be appreciated, however, that no matter how detailed the foregoing appears in text, the preferred embodiments are practiced in many ways. As is also stated above, it should be noted that the use of particular terminology when describing certain features or aspects of the preferred embodiments should not be taken to imply that the terminology is being re-defined herein to be restricted to including any specific characteristics of the features or

aspects of the preferred embodiments with which that terminology is associated.

While preferred embodiments have been shown and described herein, it will be obvious to those skilled in the art that such embodiments are provided by way of example only. Numerous variations, changes, and substitutions will now occur to those skilled in the art without departing from the preferred embodiments. It should be understood that various alternatives to the embodiments described herein could be employed in practice. It is intended that the following claims define the scope of the preferred embodiment and that methods and structures within the scope of these claims and their equivalents be covered thereby.

WHAT IS CLAIMED IS:

1. A method for controlling a continuously variable transmission having a ball-planetary variator (CVP), the CVP having a first traction ring and a second traction ring each in contact with a plurality of balls, wherein the first traction ring contacts each ball at a first contact patch, and the second traction ring contacts each balls at a second contact patch, the method comprising:

estimating a first contact patch temperature of the first contact patch;

estimating a second contact patch temperature of the second contact patch; and

commanding a CVP ratio based at least in part on the first contact patch temperature and the second contact patch temperature.

2. The method of Claim 1, further comprising determining an engine torque limit based at least in part on the first contact patch temperature and the second contact patch temperature.

3. The method of Claim 1, wherein estimating a first contact patch temperature of the first contact patch and estimating a second contact patch temperature of the second contact patch include using a model-based estimator.

4. The method of Claim 1, wherein estimating a first contact patch temperature of the first contact patch and estimating a second contact patch temperature of the second contact patch includes using an analytical estimator.

5. The method of Claim 1, wherein estimating a first contact patch temperature of the first contact patch and estimating a second contact patch temperature of the second contact patch includes using a model-based estimator and an analytical estimator.

6. The method of Claim 4, wherein using the analytical estimator further comprises providing an initial contact patch temperature based at least in part on an oil sump temperature and an ambient temperature using a cooling dynamics model.

7. The method of Claim 4, wherein using the analytical estimator further comprises using a contact patch delta temperature module.

8. The method of Claim 7, wherein using the contact patch delta temperature module further includes:

determining an entrainment velocity at each contact patch based at least in part on an input speed and a commanded CVP ratio using a rolling entrainment velocity module,

providing a plurality of parameters indicative of size and shape of each contact patch based at least in part on an input torque to the CVP using a contact patch geometry module,

determining a specific power loss for each contact patch based at least in part on the plurality of parameters indicative of size and shape and the CVP ratio;, and

determining a change in a contact patch temperature for each traction ring based at least in part on the specific power loss for each contact patch using a traction ring contact patch delta temperature module.

9. The method of Claim 4, wherein the using analytical estimator includes using a CVP lubrication system flow model.

10. The method of Claim 8, wherein using the analytical estimator further comprises determining the first contact patch temperature and the second contact patch temperature based at least in part on the change in contact patch temperature for each traction ring determined by the traction ring contact patch delta temperature module using a contact patch temperature module.

11. The method of Claim 8, wherein the rolling entrainment velocity module calculates an actual CVP ratio and a CVP droop.

12. The method of Claim 11, wherein the entrainment velocity at each contact patch is based at least in part on the CVP droop.

13. The method of Claim 3, wherein using the model-based estimator further comprises:

determining the first contact patch temperature based at least in part on a heat loss at the first contact patch using a first traction ring transfer function; and

determining the second contact patch temperature based at least in part on a heat loss at the second contact patch using a second traction ring transfer function.

14. The method of Claim 13, wherein using the model-based estimator further comprises using a first traction sun transfer function and a second traction sun transfer function.

15. The method of Claim 14, wherein the first traction sun transfer function determines a first traction sun contact temperature based at least in part on a heat loss at a contact patch between a first traction sun and the balls.

16. The method of Claim 15, wherein the second traction sun transfer function determines a second traction sun contact temperature based at least in part on a heat loss at a contact patch between a second traction sun and the balls.

17. The method of Claim 14, wherein the first traction ring transfer function, the first traction sun transfer function, the second traction ring transfer function, and the second traction sun transfer function receive a plurality of transfer function coefficients from a multiple dimension look-up table.

18. The method of Claim 5, wherein using the contact patch temperature module further comprises providing a weighting coefficient based at least in part on an input speed and an input torque of the CVP using a weighting coefficients look-up table.

19. The method of Claim 2, wherein determining an engine torque limit further comprises determining a CVP ratio limit using a CVP ratio control module.

20. The method of Claim 2, wherein determining an engine torque limit further comprises determining a fault status using a thermal limit control module.

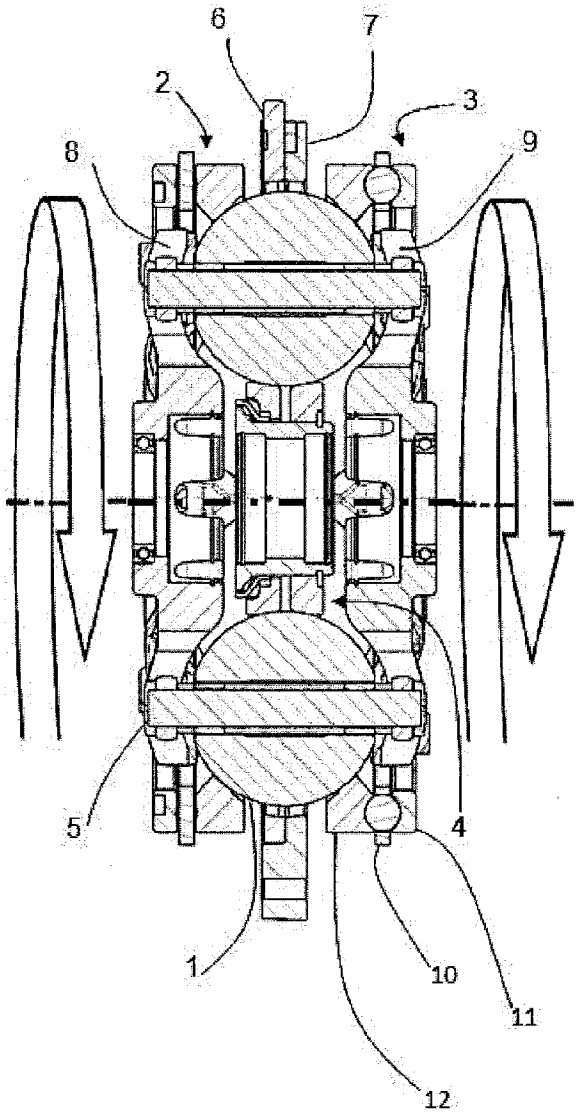


Figure 1

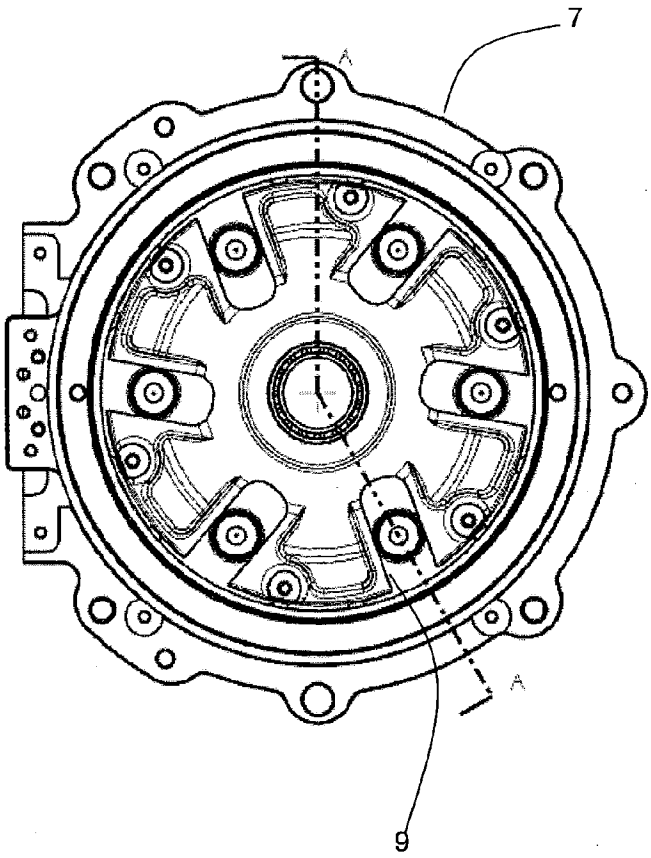


Figure 2

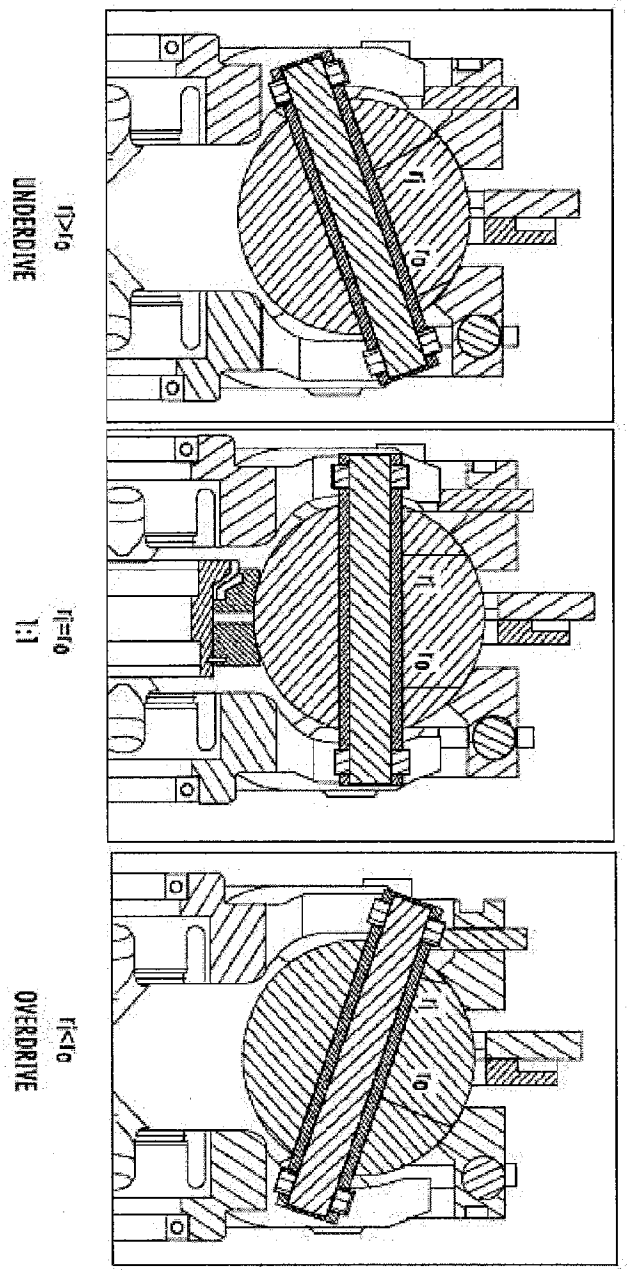


FIG. 3

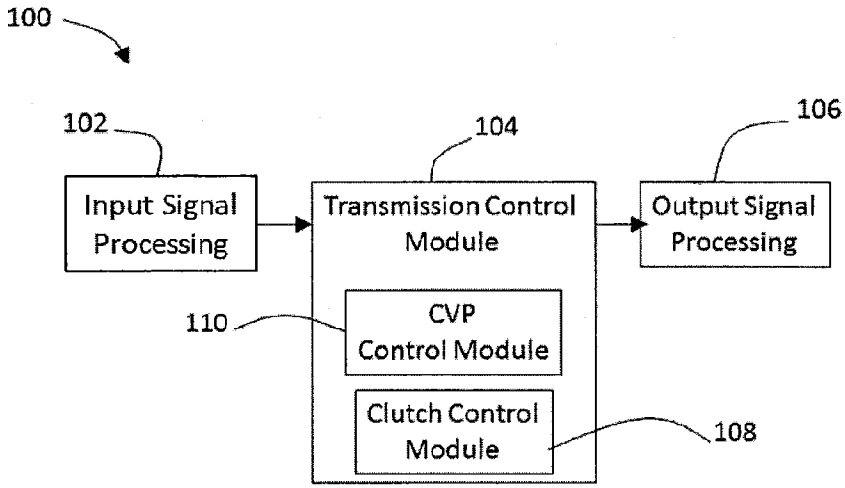


Figure 4

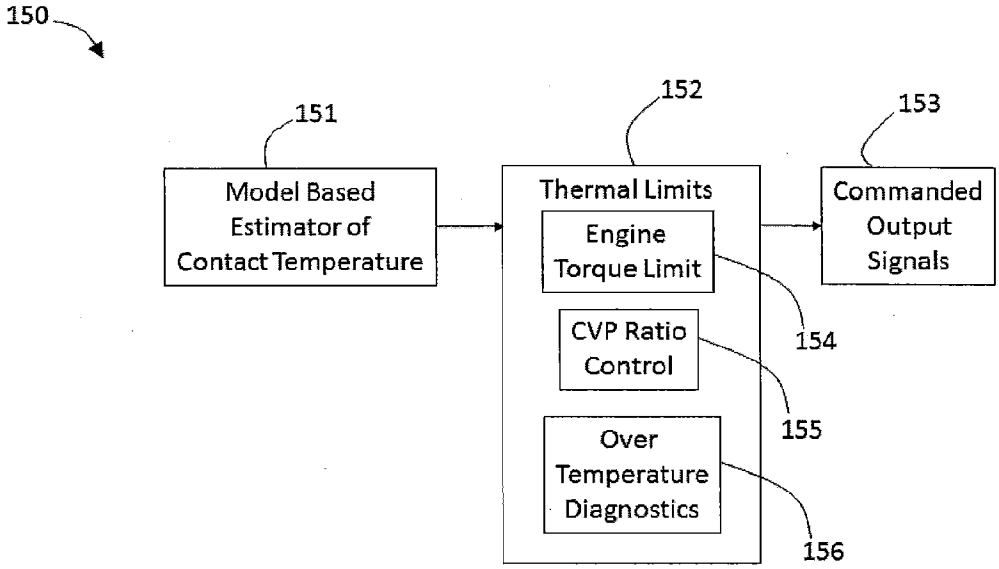


Figure 5

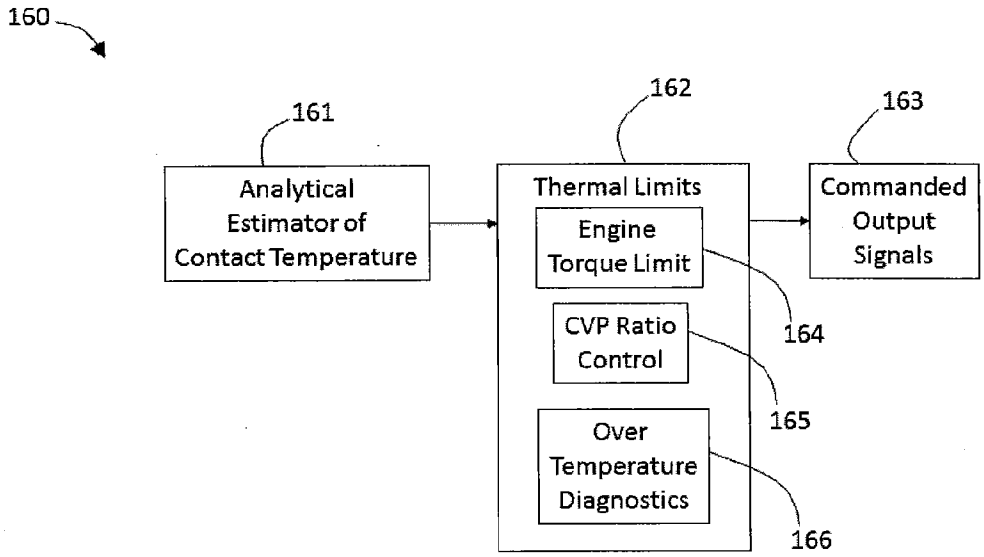


Figure 6

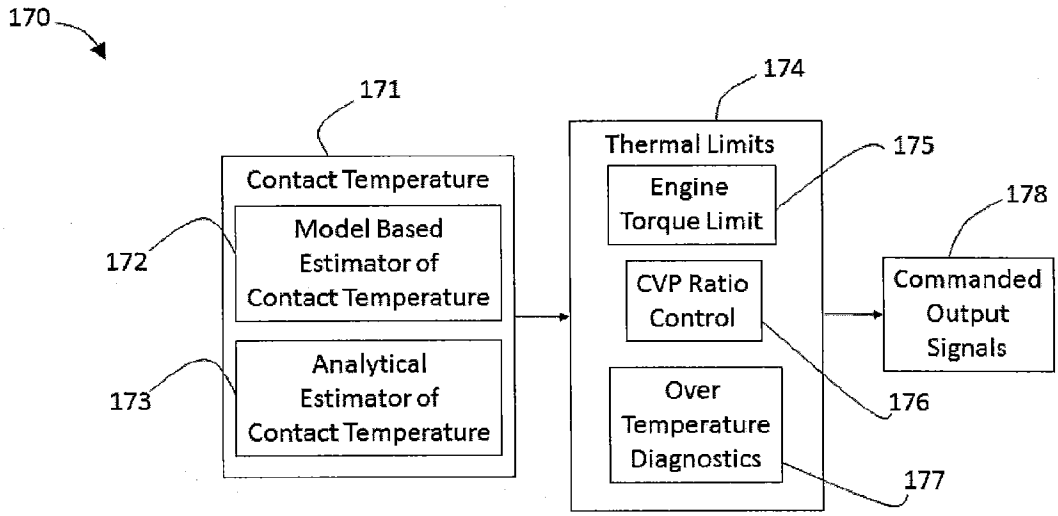


Figure 7

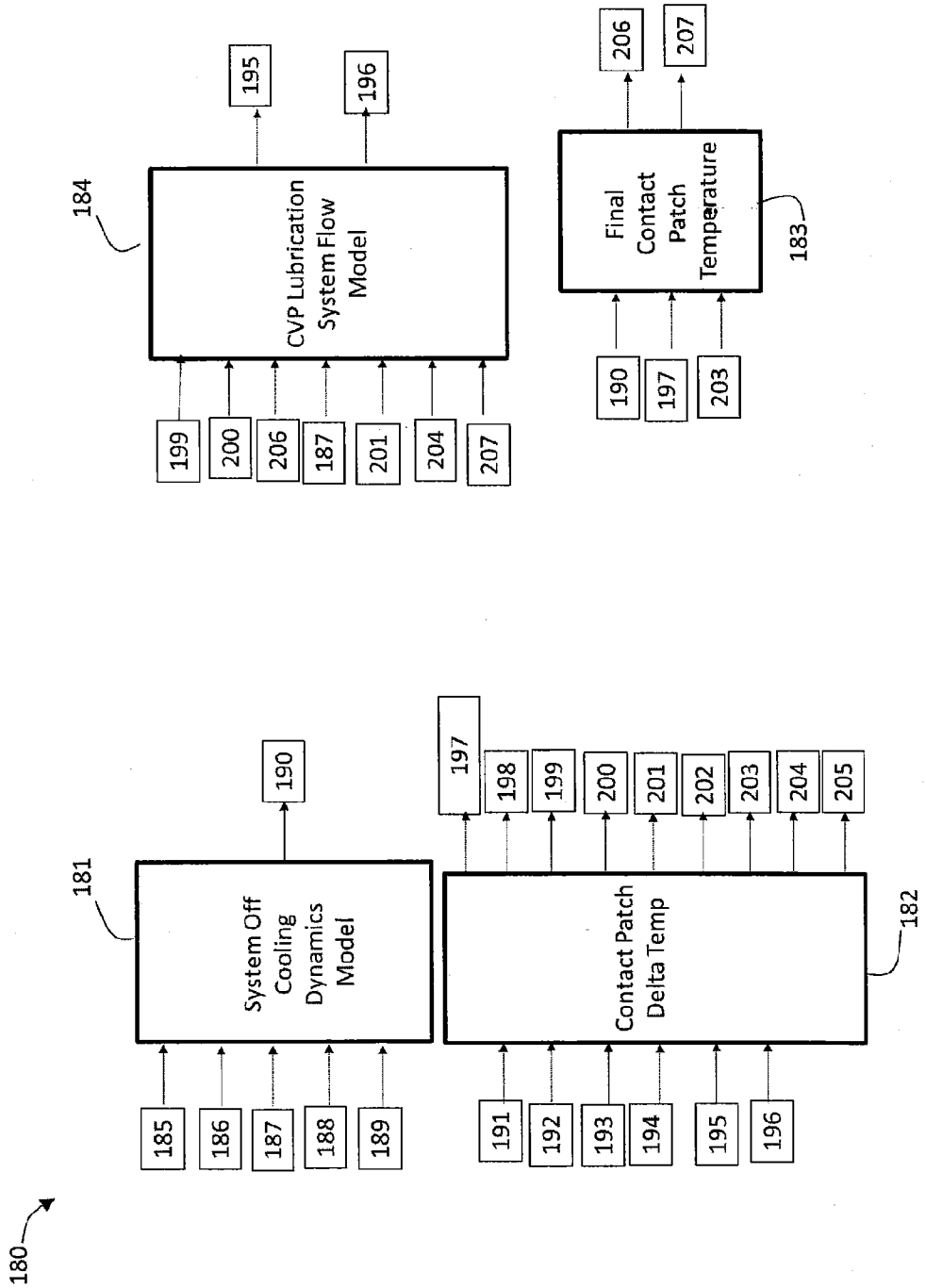

184
CVP Lubrication System Flow Model
195
196
199
200
206
187
201
204
207
183
Final Contact Patch Temperature
206
207
190
197
203
181
System Off Cooling Dynamics Model
190
185
186
187
188
189
182
Contact Patch Delta Temp
197
198
199
200
201
202
203
204
205
191
192
193
194
195
196
180

Figure 8

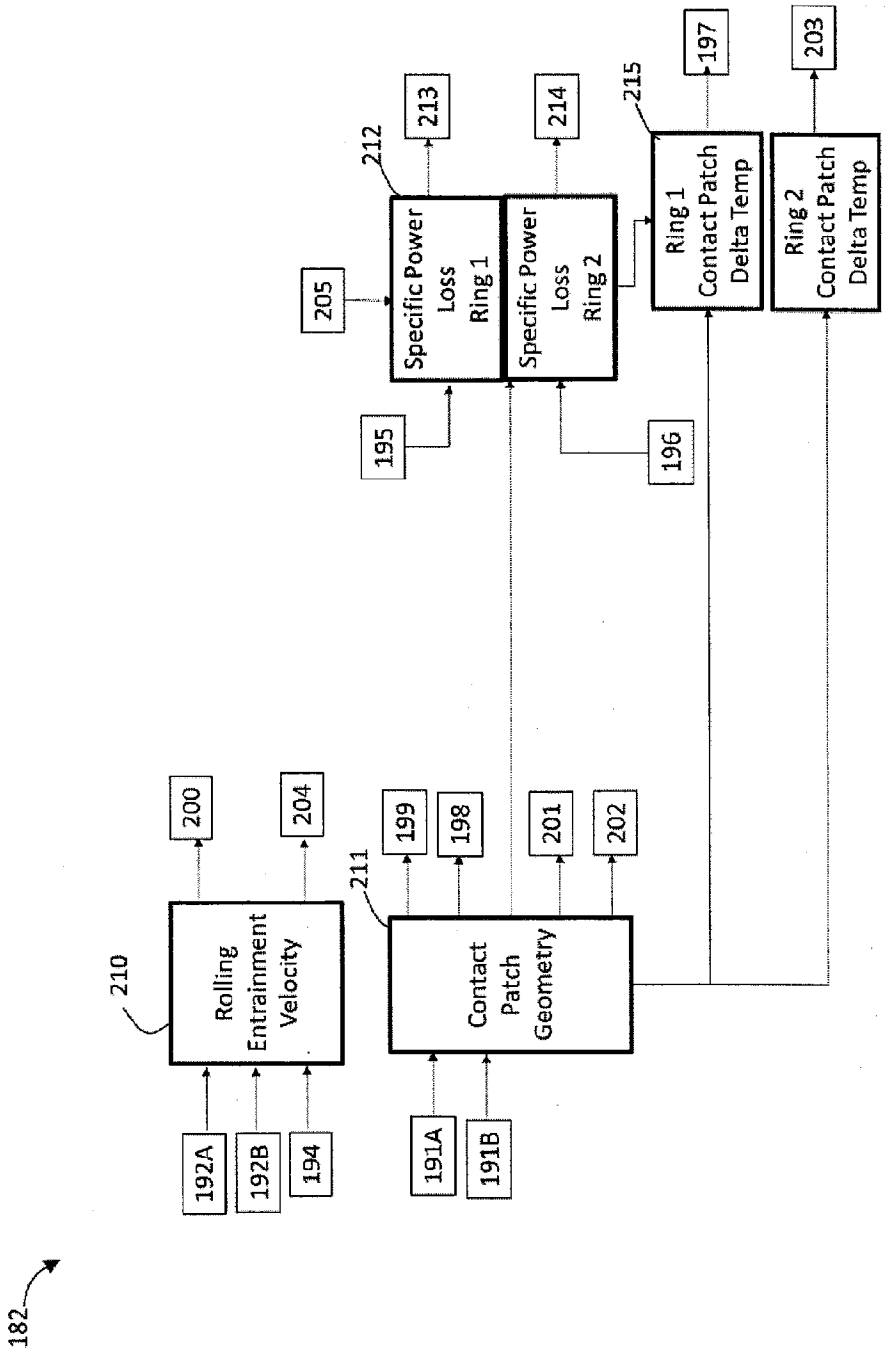

182
210
Rolling Entrainment Velocity
211
Contact Patch Geometry
212
Specific Power Loss Ring 1
Specific Power Loss Ring 2
215
Ring 1 Contact Patch Delta Temp
Ring 2 Contact Patch Delta Temp
192A
192B
194
191A
191B
195
196
205
200
204
199
198
201
202
213
214
197
203

Figure 9

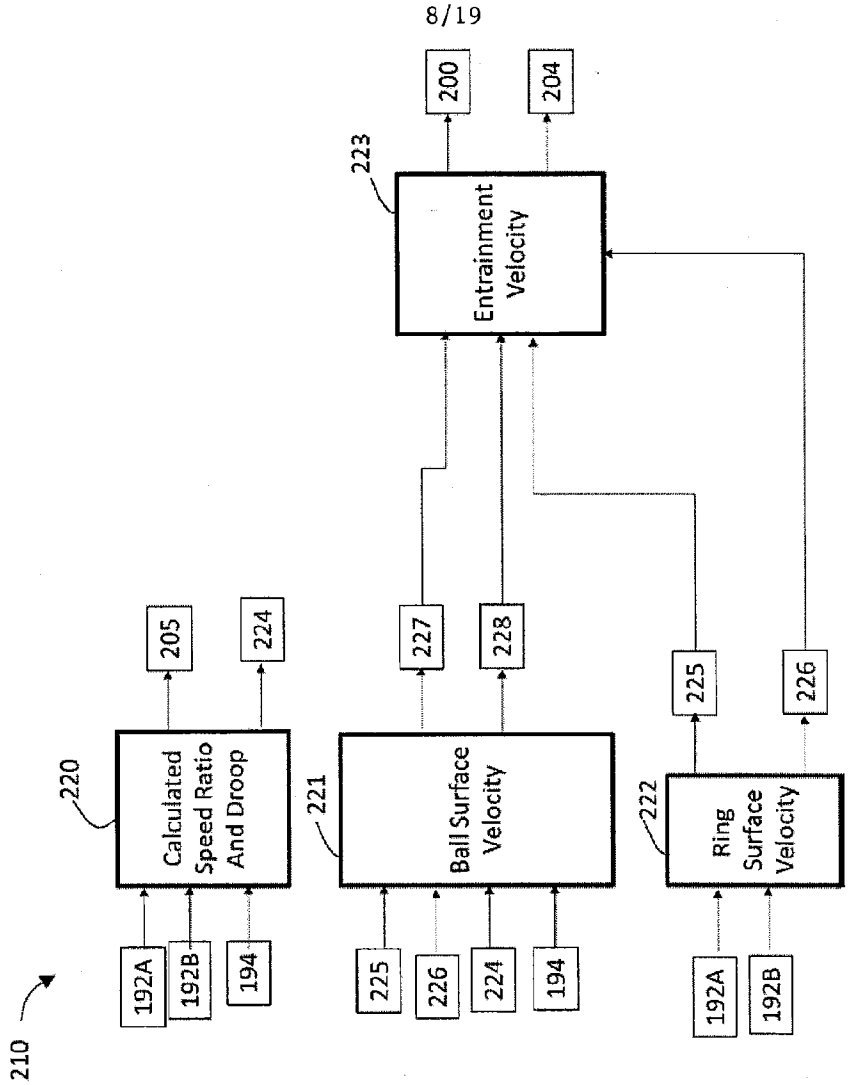

200
204
223
Entrainment Velocity
205
224
227
228
225
226
220
Calculated Speed Ratio And Droop
221
Ball Surface Velocity
222
Ring Surface Velocity
192A
192B
194
225
226
224
194
192A
192B
210

Figure 10

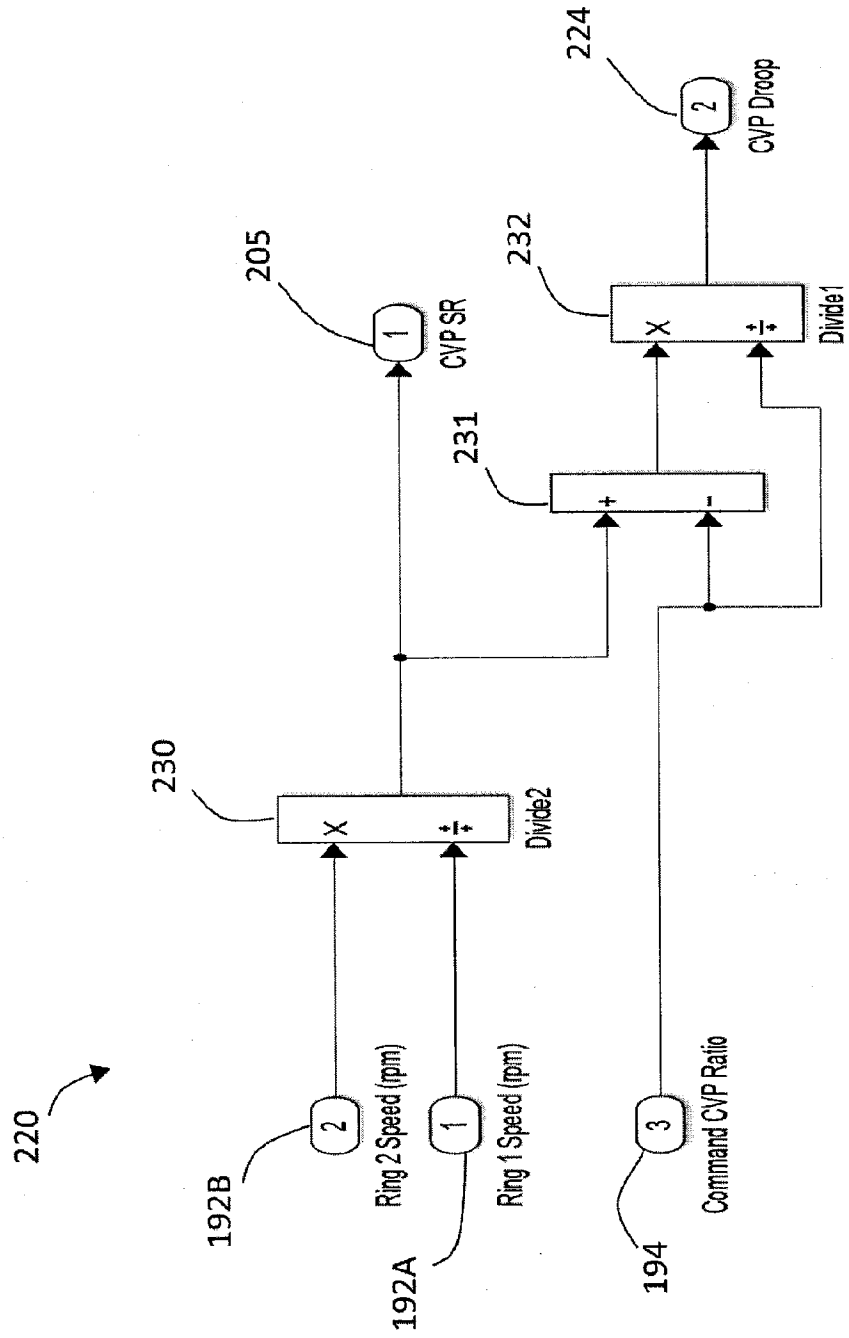

220
192B
2
Ring 2 Speed (rpm)
192A
1
Ring 1 Speed (rpm)
194
3
Command CVP Ratio
230
X
÷
Divide2
205
1
CVP SR
231
+
-
232
X
÷
Divide1
224
2
CVP Droop

Figure 11

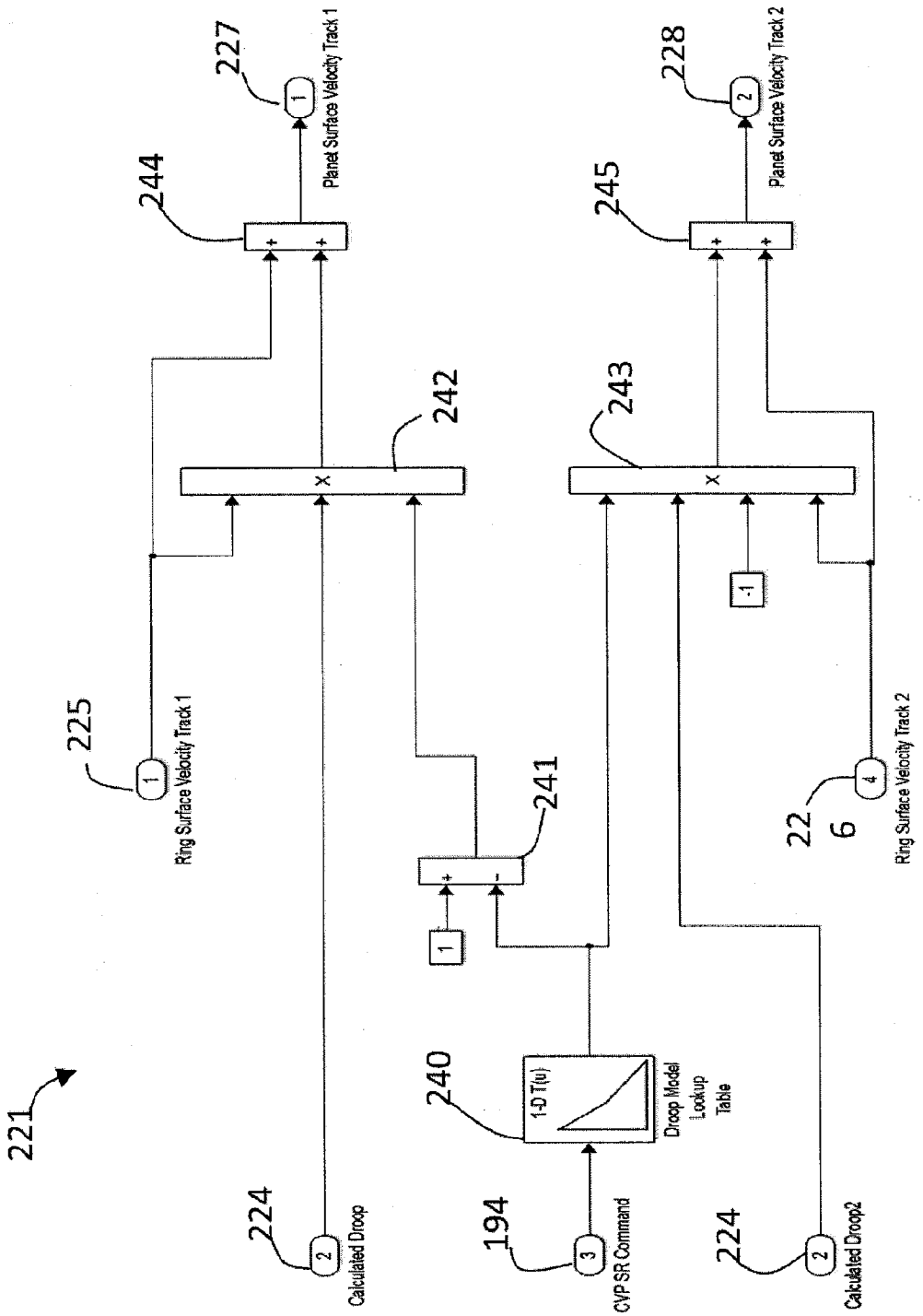

221
225
Ring Surface Velocity Track 1
227
Planet Surface Velocity Track 1
228
Planet Surface Velocity Track 2
244
245
242
243
241
240
1-D T(u)
Droop Model Lookup Table
224
Calculated Droop
194
CVP SR Command
224
Calculated Droop2
22 6
Ring Surface Velocity Track 2
-1
1

Figure 12

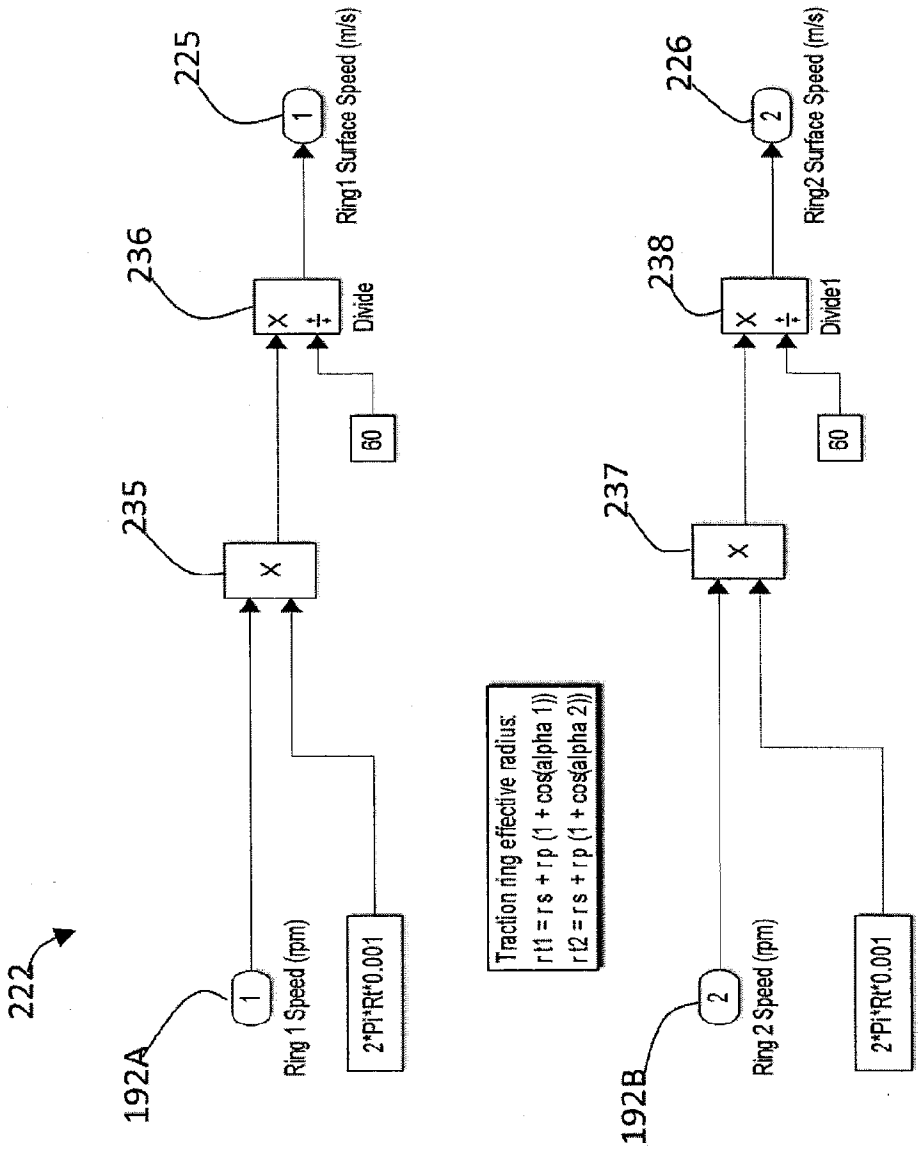

222
192A
192B
225
226
235
236
237
238
1
2
Ring 1 Speed (rpm)
Ring 2 Speed (rpm)
2*Pi*Rt*0.001
2*Pi*Rt*0.001
60
60
X
÷
Divide
Divide1
Ring1 Surface Speed (m/s)
Ring2 Surface Speed (m/s)
Traction ring effective radius:
rt1 = rs + rp (1 + cos(alpha 1))
rt2 = rs + rp (1 + cos(alpha 2))

Figure 13

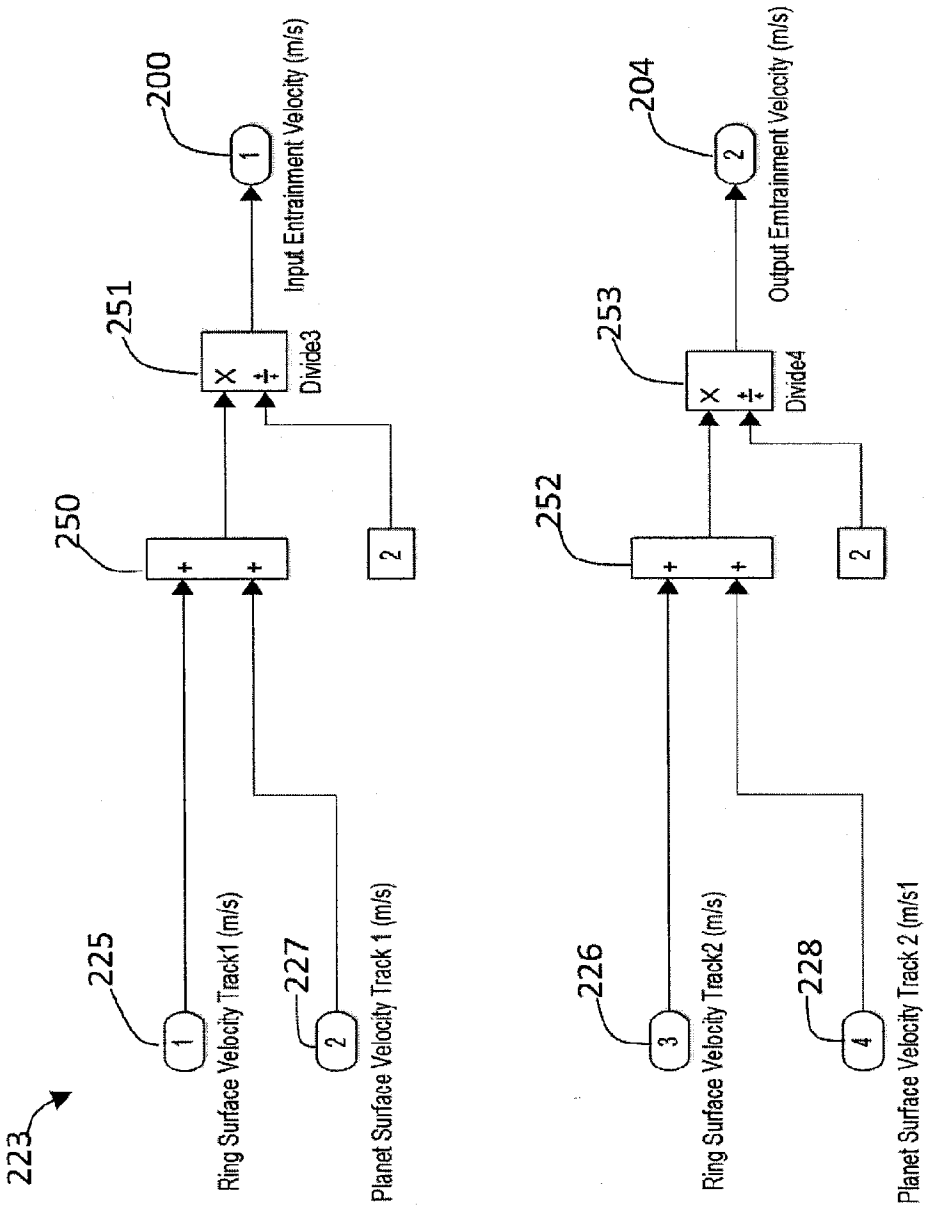

223
225
Ring Surface Velocity Track1 (m/s)
227
Planet Surface Velocity Track 1 (m/s)
250
251
Divide3
Input Entrainment Velocity (m/s)
200
252
226
Ring Surface Velocity Track2 (m/s)
228
Planet Surface Velocity Track 2 (m/s1
253
Divide4
Output Entrainment Velocity (m/s)
204

Figure 14

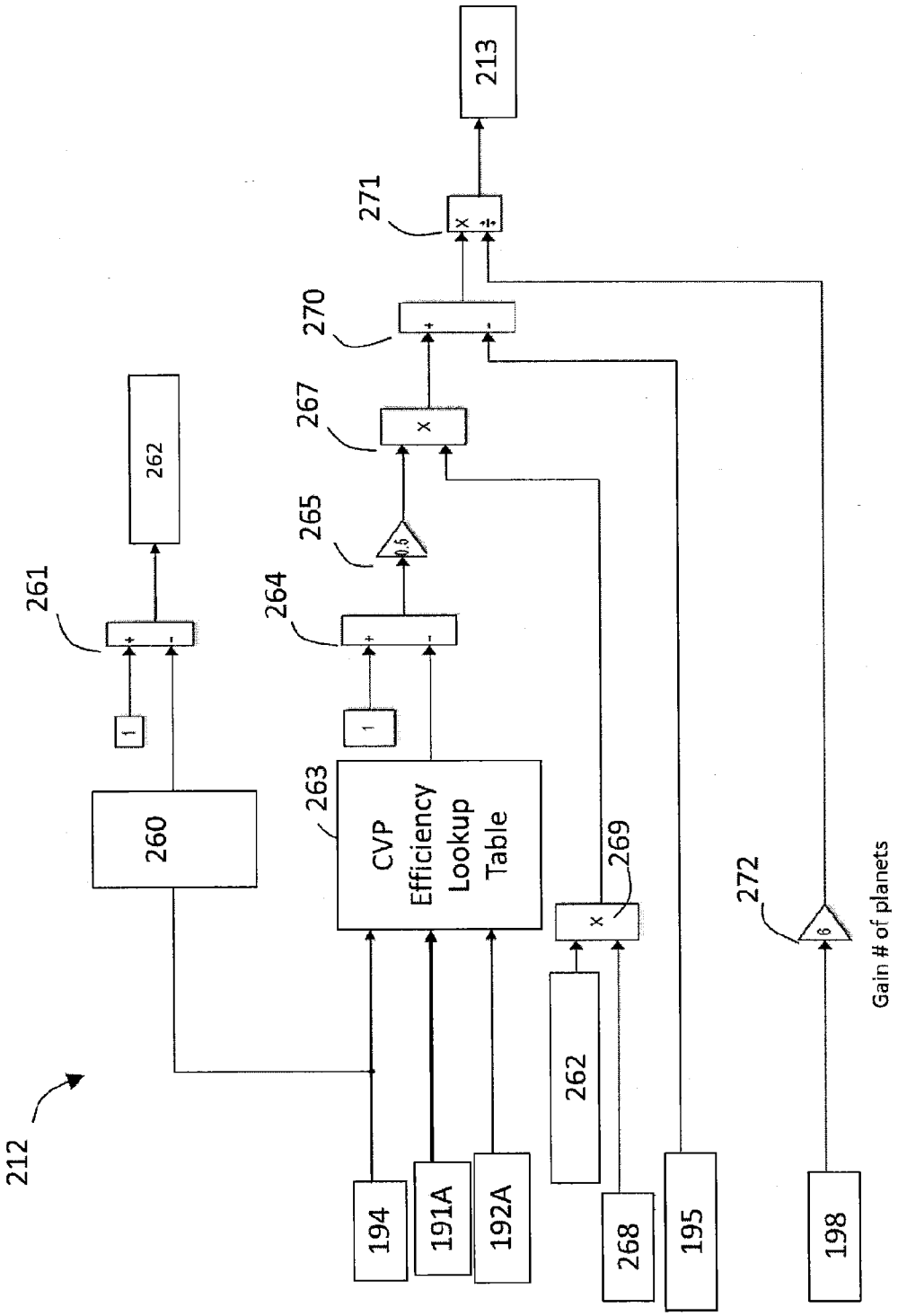

213
271
270
267
265
264
261
262
263
CVP Efficiency Lookup Table
260
269
272
Gain # of planets
212
194
191A
192A
262
268
195
198

Figure 15

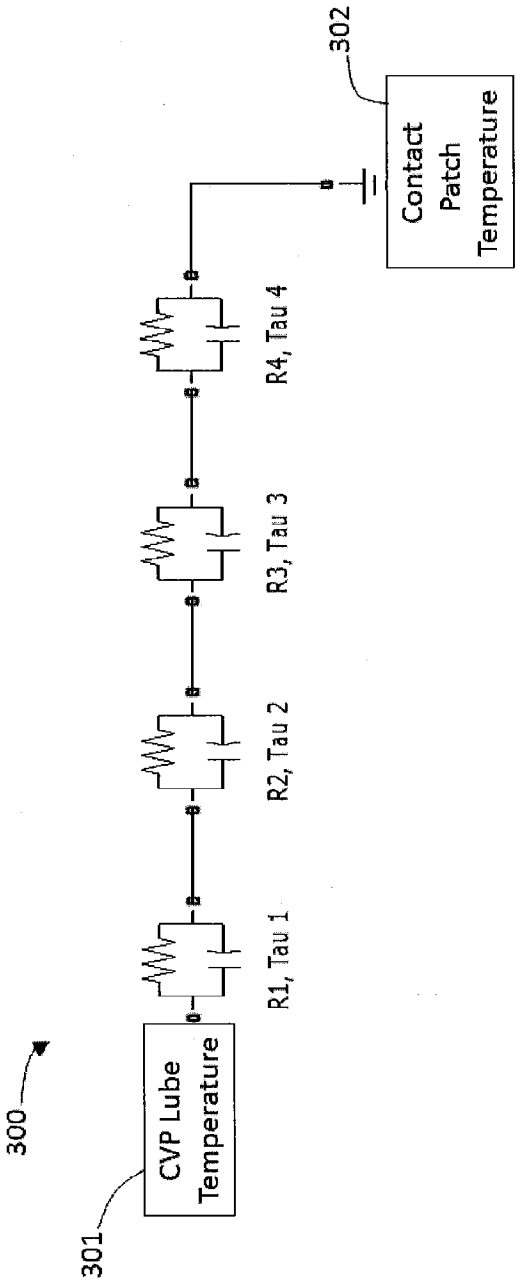

302
Contact Patch Temperature
R4, Tau 4
R3, Tau 3
R2, Tau 2
R1, Tau 1
CVP Lube Temperature
300
301

Figure 16

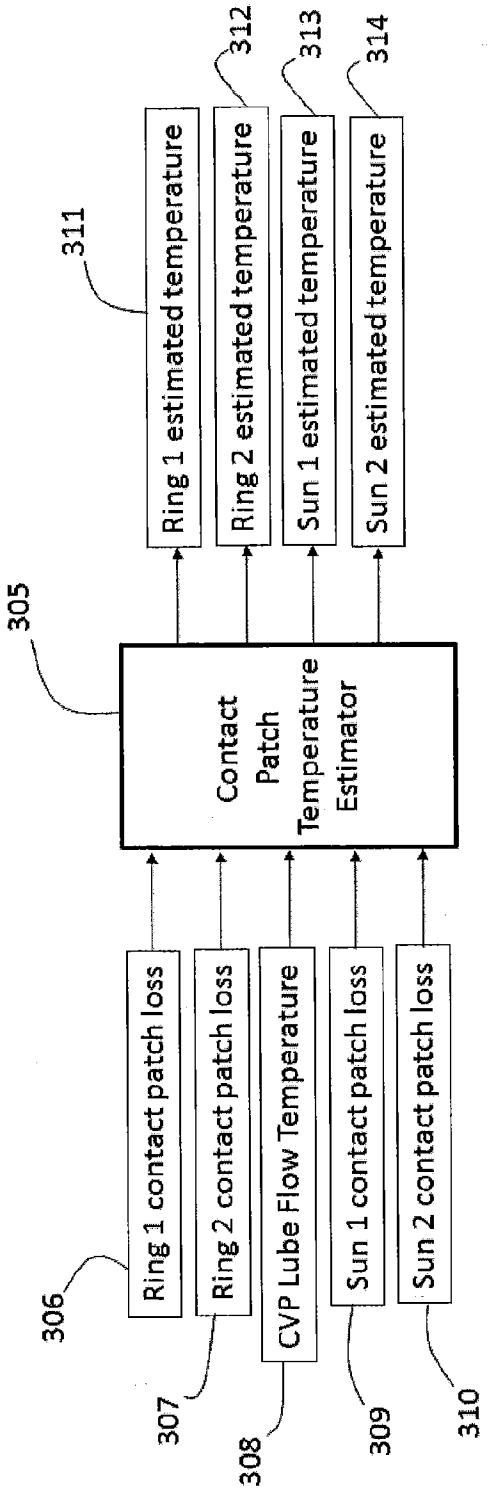

Ring 1 contact patch loss
Ring 2 contact patch loss
CVP Lube Flow Temperature
Sun 1 contact patch loss
Sun 2 contact patch loss
Contact Patch Temperature Estimator
Ring 1 estimated temperature
Ring 2 estimated temperature
Sun 1 estimated temperature
Sun 2 estimated temperature
305
306
307
308
309
310
311
312
313
314

Figure 17

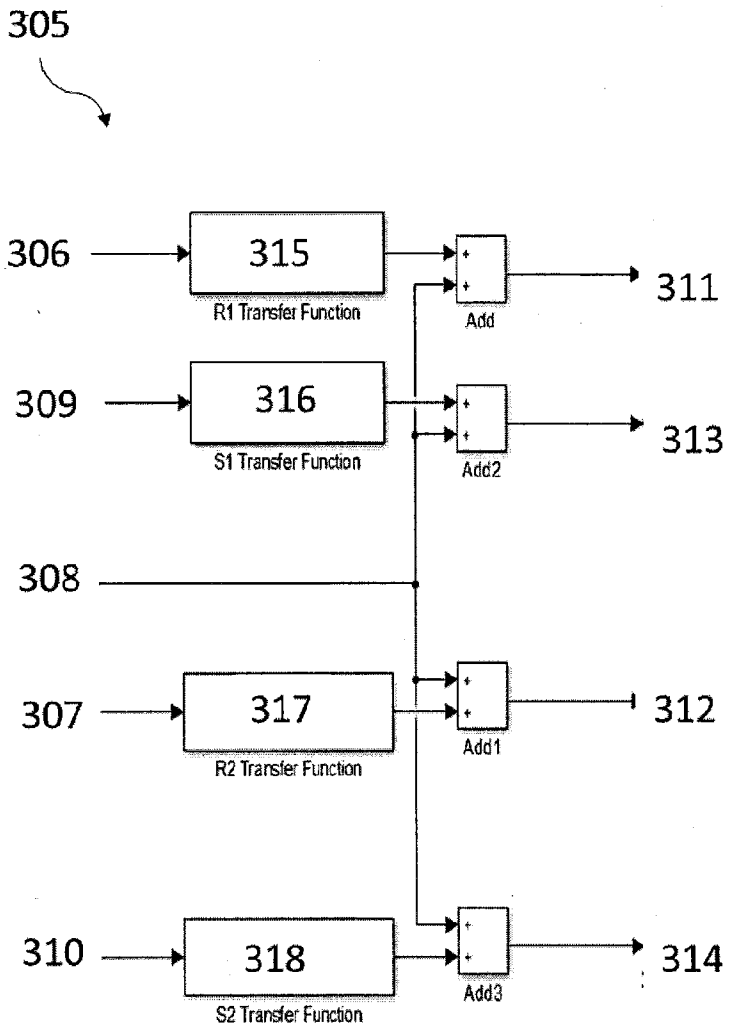

305
306
315
R1 Transfer Function
Add
311
309
316
S1 Transfer Function
Add2
313
308
307
317
R2 Transfer Function
Add1
312
310
318
S2 Transfer Function
Add3
314

Figure 18

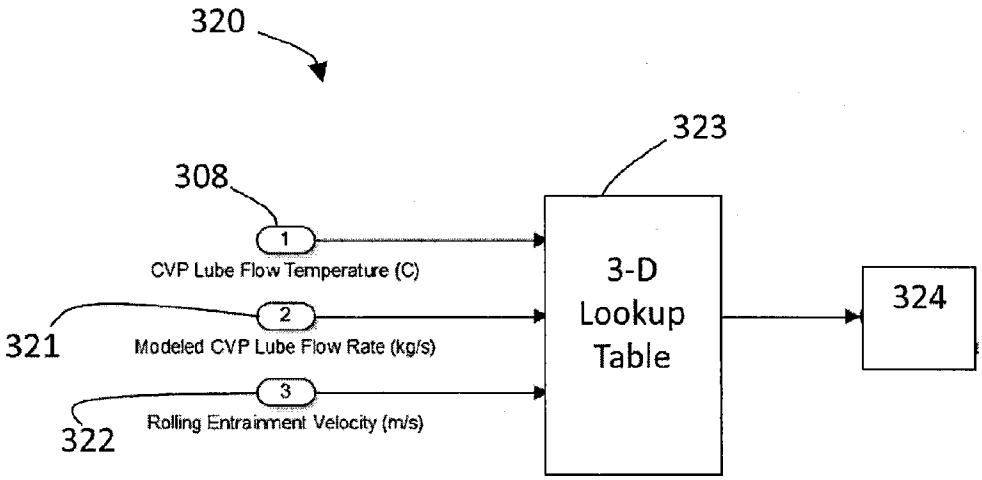

320
323
308
1
CVP Lube Flow Temperature (C)
2
321
Modeled CVP Lube Flow Rate (kg/s)
3
322
Rolling Entrainment Velocity (m/s)
3-D
Lookup
Table
324

Figure 19

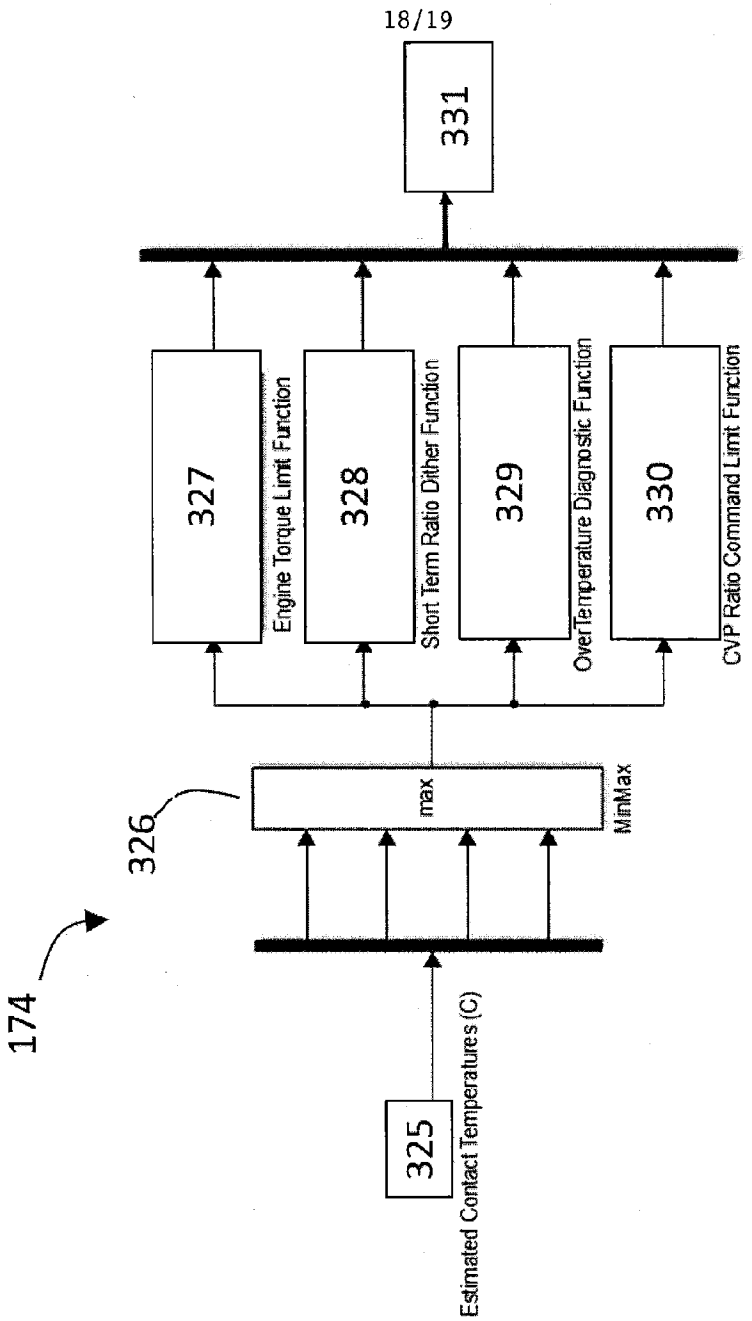

331
327
Engine Torque Limit Function
328
Short Term Ratio Dither Function
329
OverTemperature Diagnostic Function
330
CVP Ratio Command Limit Function
326
max
MinMax
174
325
Estimated Contact Temperatures (C)

Figure 20

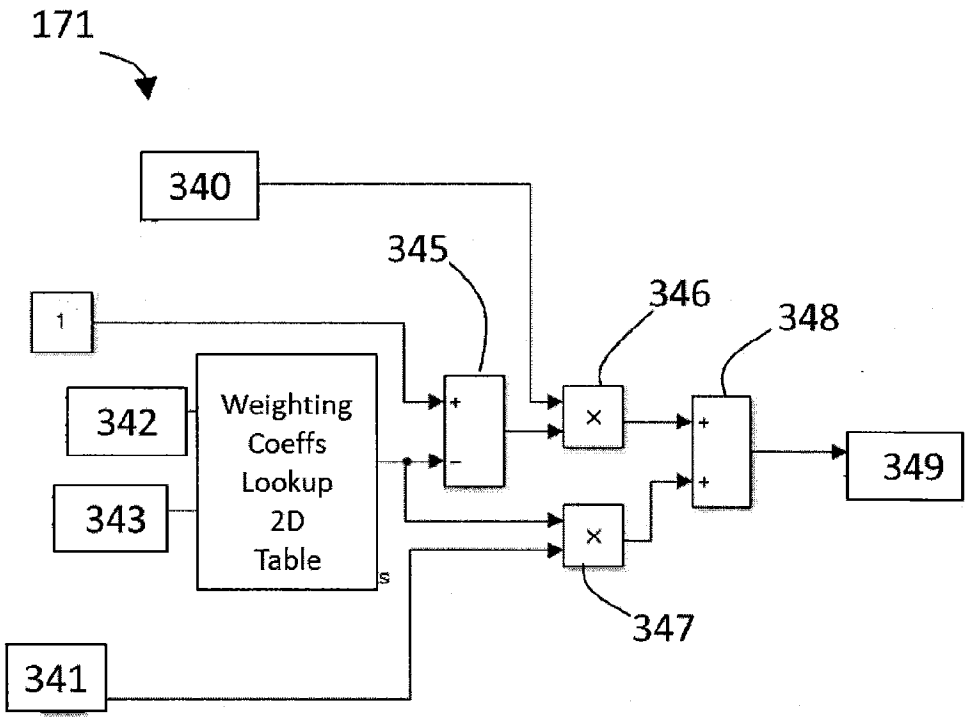

171
340
345
346
348
1
342
Weighting
Coeffs
Lookup
2D
Table
343
349
347
341

Figure 21

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/059461

A. CLASSIFICATION OF SUBJECT MATTER
INV. F16H61/664
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F16H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/029676 A1 (TAKETSUNA YASUJI [JP] ET AL) 12 February 2004 (2004-02-12) paragraphs [0032], [0033]; figures	1-20
X	DATABASE WPI Week 201274 Thomson Scientific, London, GB; AN 2012-P01209 XP002778129, -& JP 2012 211612 A (NIPPON SEIKO KK) 1 November 2012 (2012-11-01) abstract; figures	1-20
X	US 5 807 206 A (OKAZAKI MAKOTO [JP]) 15 September 1998 (1998-09-15) column 7 - lines 12-46; figures	1-20

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
12 February 2018	23/02/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Meritano, Luciano

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/059461

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 620 076 B1 (KAWAMURA YASUTAKA [JP] ET AL) 16 September 2003 (2003-09-16) column 7, lines 45-65	1-20
X	US 5 643 132 A (INOUE EIJI [JP]) 1 July 1997 (1997-07-01) column 7, lines 1-37; figures	1-20

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Information on patent family members

International application No
PCT/US2017/059461

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US 5643132 A	01-07-1997	NONE	