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(54) **ARTIFICIAL OUTPUT REFERENCE FOR MODEL PREDICTIVE CONTROL**

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(51) **Int. Cl.**

F02D 37/02 (2006.01)
B60W 10/06 (2006.01)
F02D 41/14 (2006.01)

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CPC ***F02D 37/02*** (2013.01); ***B60W 10/06*** (2013.01); ***F02D 41/1401*** (2013.01); ***F02D 41/1497*** (2013.01); *F02D 2041/1412* (2013.01); *F02D 2041/1433* (2013.01); *F02D 2200/1004* (2013.01); *F02D 2250/18* (2013.01); *F02D 2250/22* (2013.01); *F02N 2300/2006* (2013.01)

(58) **Field of Classification Search**

CPC F02D 37/02; F02D 41/14; F02D 41/1401; F02D 41/1497; F02D 241/1433; F02D 2041/1412; F02D 2250/18; F02D 2250/22; B60W 10/60

See application file for complete search history.

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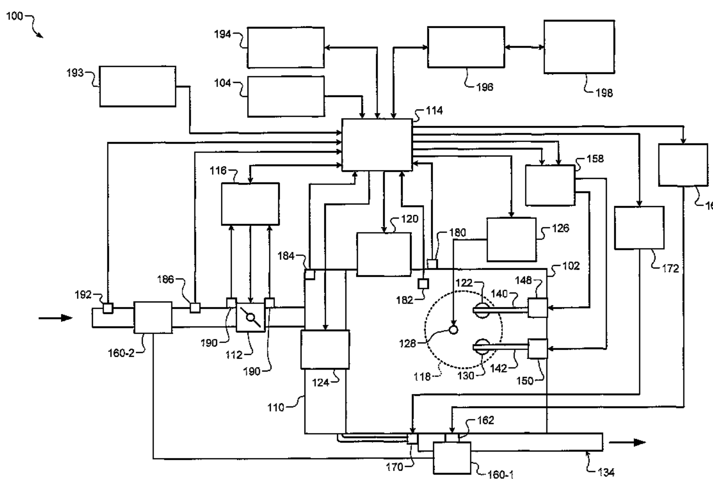
(57) **ABSTRACT**

A control system includes a control module that receives a first request corresponding to a control value for at least one of a plurality of actuators, selectively receives a second request associated with a predicted future control value for at least one of the plurality of actuators, determines a target value for the actuator based on the first request if the second request was not received, and generates a reference signal representing the second request if the second request was received. The reference signal indicates at least one of a predicted increase in the control value and a predicted decrease in the control value. A model predictive control module receives the reference signal and adjusts one of the plurality of actuators associated with the predicted future control value based on the reference signal.

19 Claims, 6 Drawing Sheets



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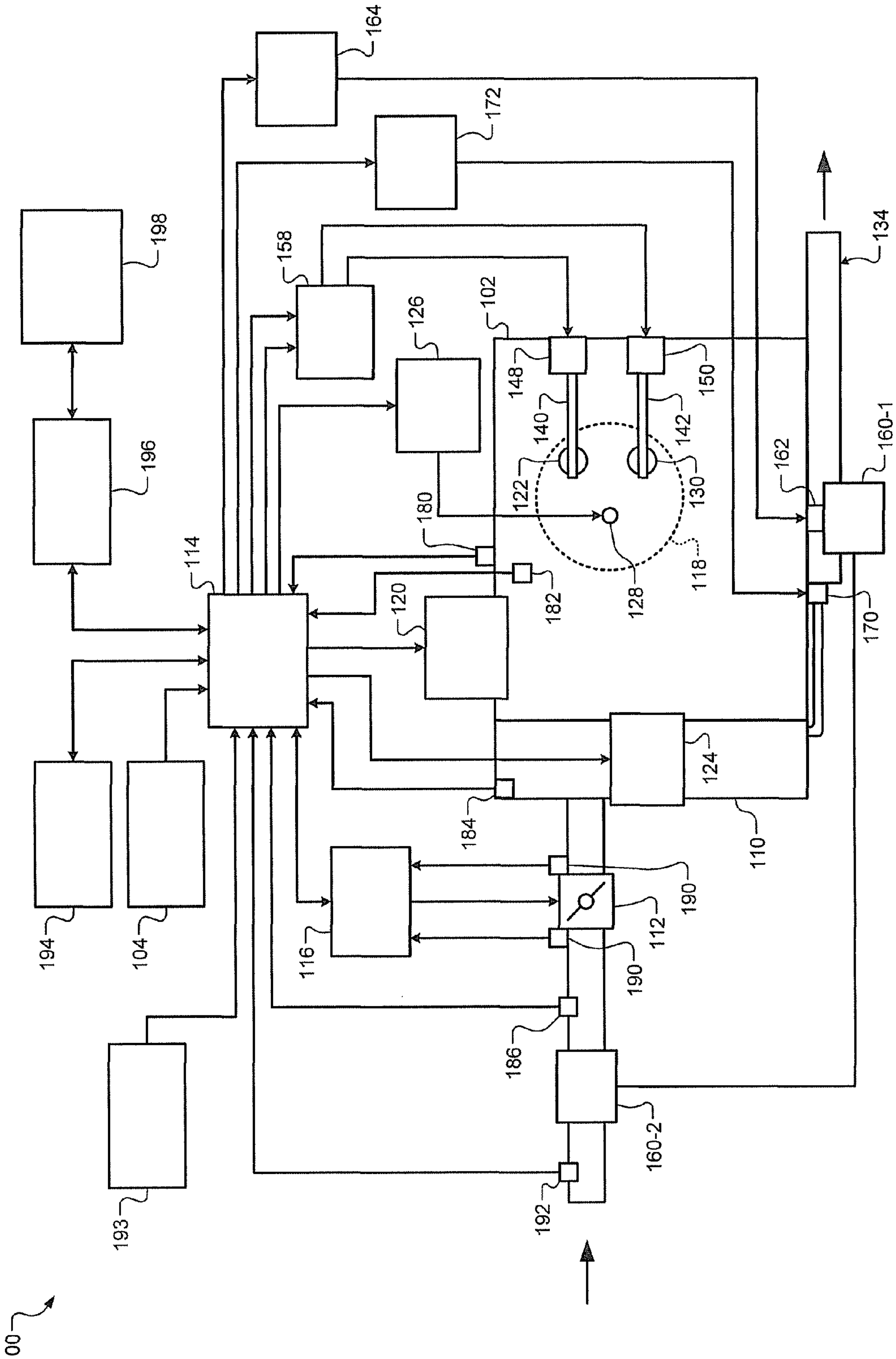
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FIG. 1

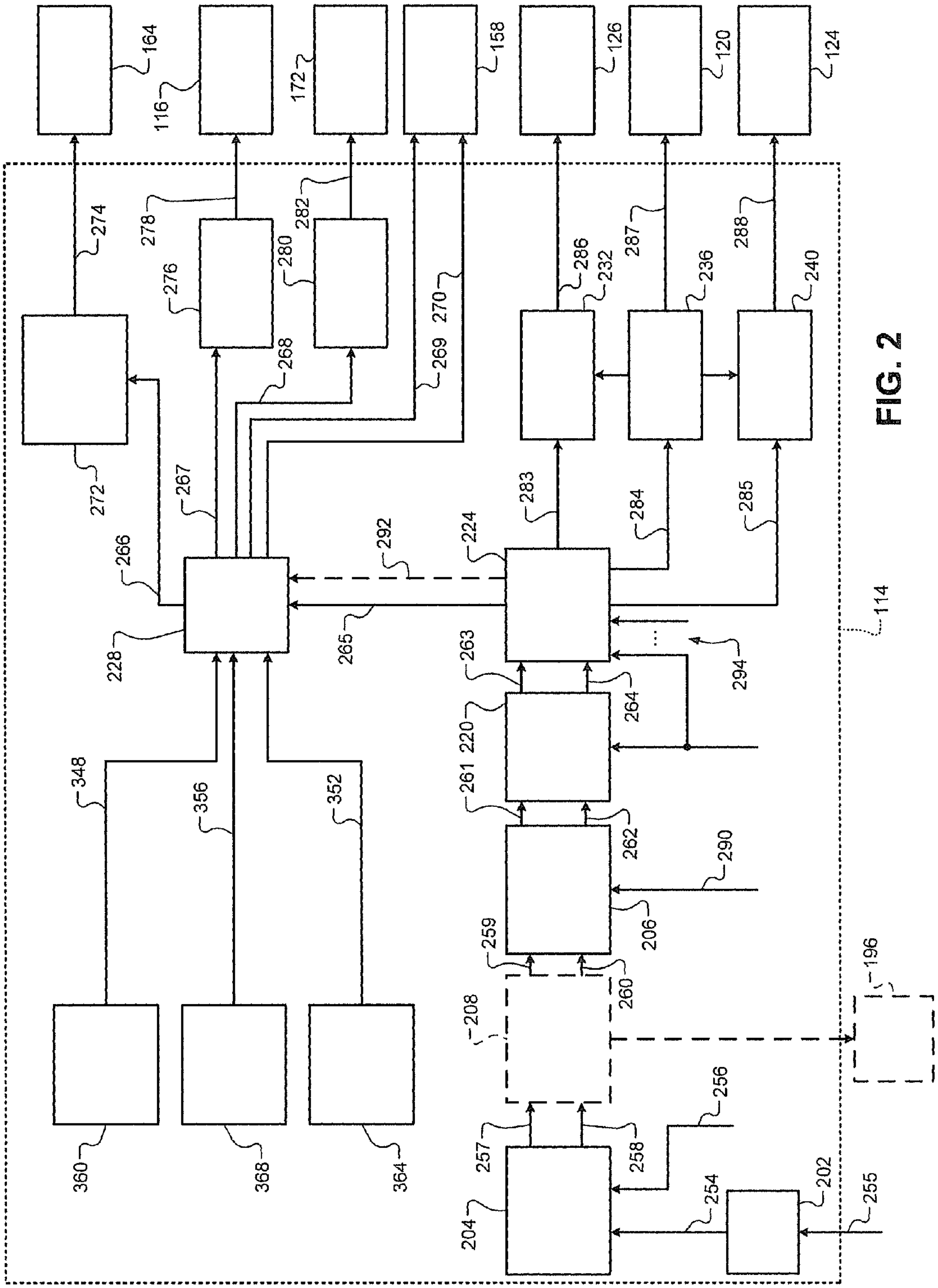
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FIG. 2

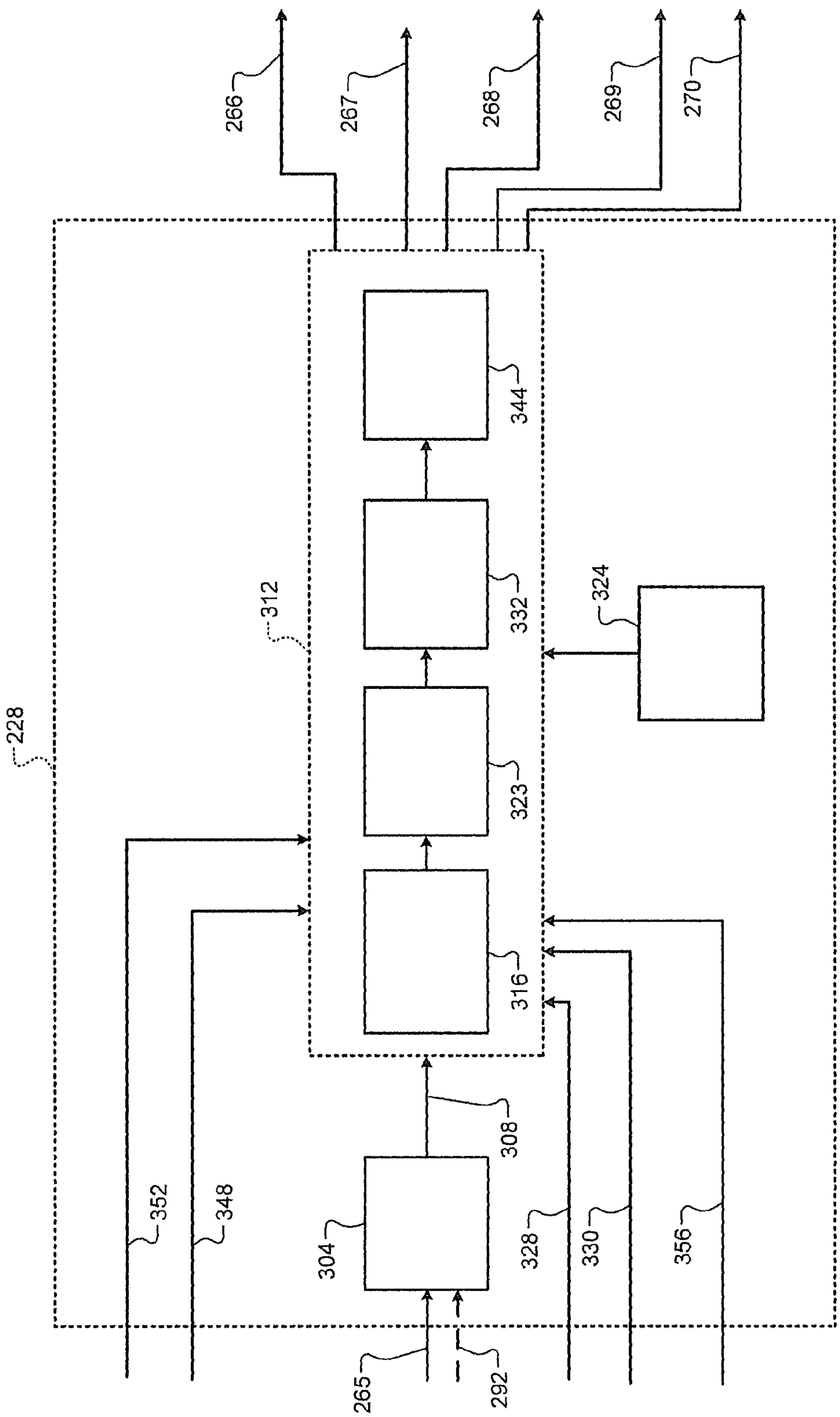
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FIG. 3

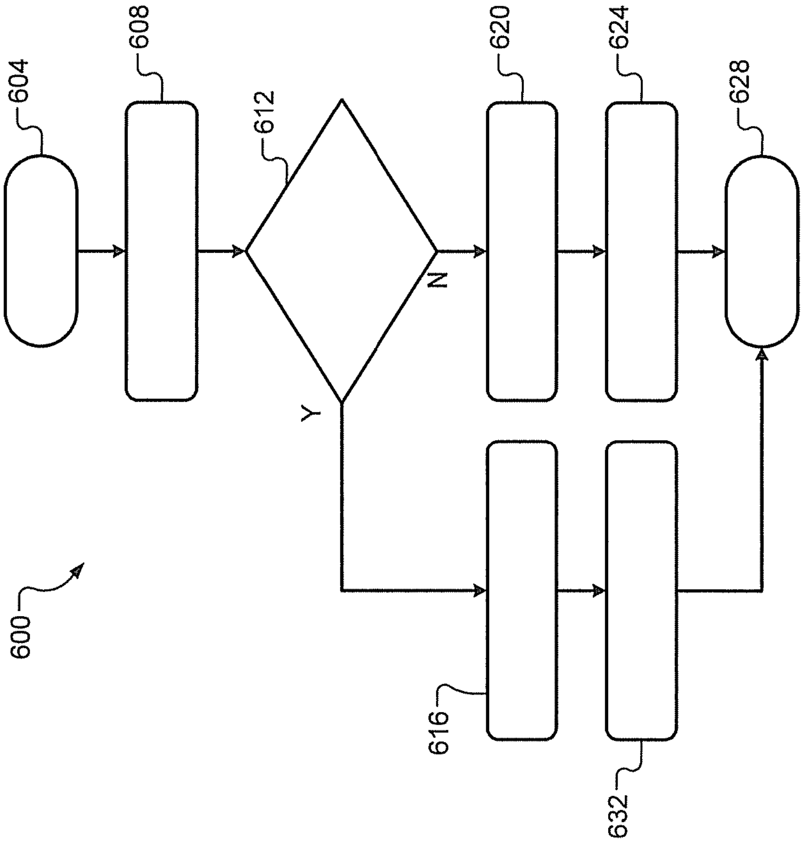
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FIG. 6

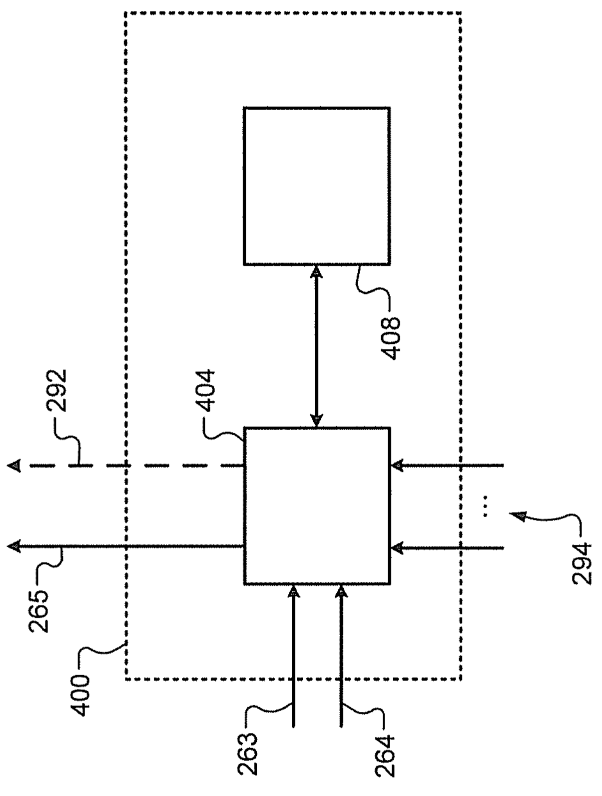
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FIG. 4

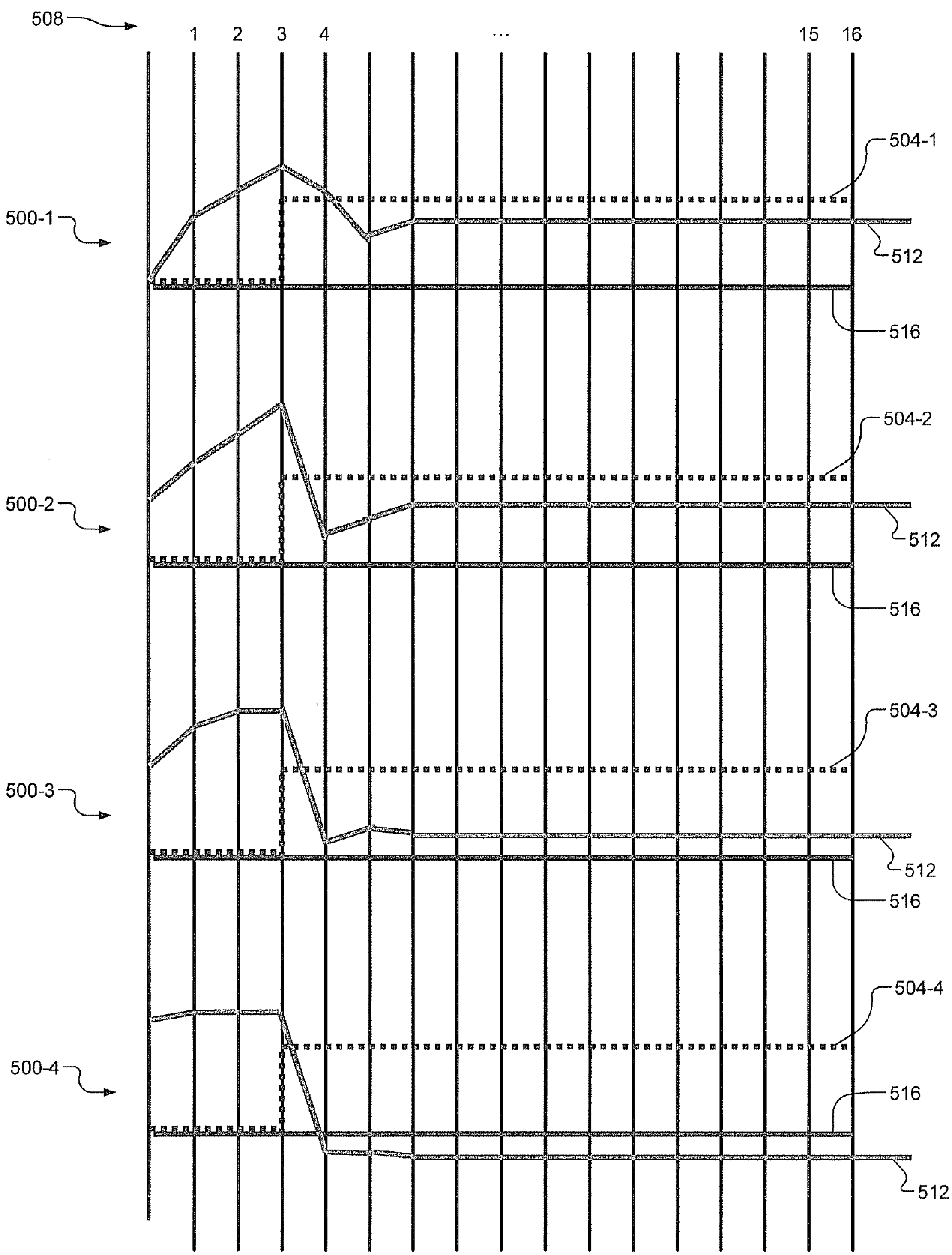
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FIG. 5A

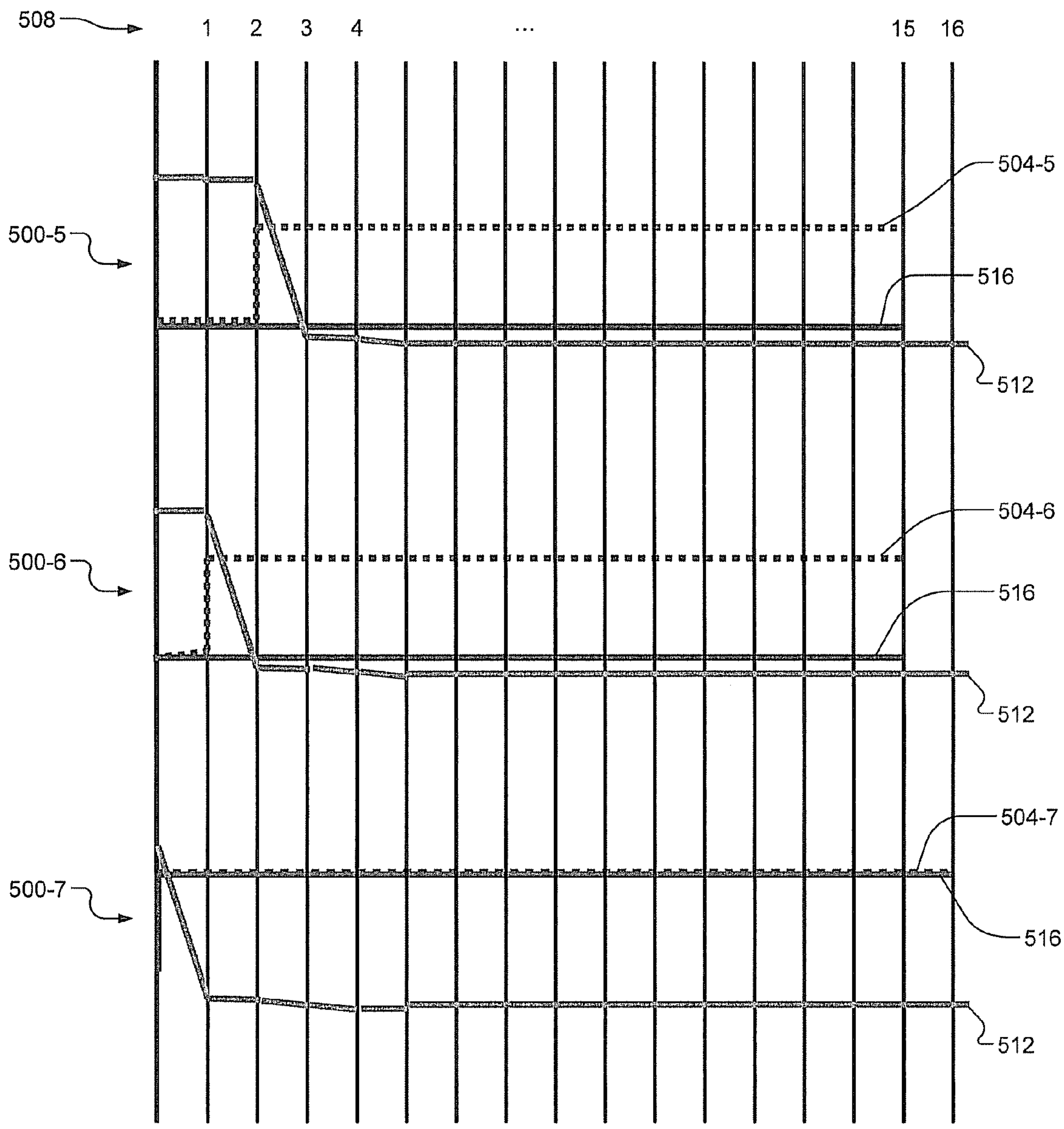
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FIG. 5B

ARTIFICIAL OUTPUT REFERENCE FOR MODEL PREDICTIVE CONTROL

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to U.S. patent application Ser. No. 14/225,502 filed on Mar. 26, 2014, Ser. No. 14/225,516 filed on Mar. 26, 2014, Ser. No. 14/225,569 filed on Mar. 26, 2014, Ser. No. 14/225,626 filed on Mar. 26, 2014, Ser. No. 14/225,896 filed on Mar. 26, 2014, Ser. No. 14/225,531 filed on Mar. 26, 2014, Ser. No. 14/225,507 filed on Mar. 26, 2014, Ser. No. 14/225,808 filed on Mar. 26, 2014, Ser. No. 14/225,587 filed on Mar. 26, 2014, Ser. No. 14/225,492 filed on Mar. 26, 2014, Ser. No. 14/226,006 filed on Mar. 26, 2014, Ser. No. 14/226,121 filed on Mar. 26, 2014, Ser. No. 14/225,496 filed on Mar. 26, 2014, and Ser. No. 14/225,891 filed on Mar. 26, 2014. The entire disclosure of the above applications are incorporated herein by reference.

FIELD

The present disclosure relates to engine control systems and methods for vehicles.

BACKGROUND

The background description provided here is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent it is described in this background section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

Control systems, such as engine control systems, include a plurality of actuators that are controlled to vary operating parameters. Example actuators in an engine control system include, but are not limited to, a throttle valve, spark plug actuators, cam phasers, exhaust gas recirculation valves, a wastegate, cylinder valves, or any other component for varying engine parameters. The engine control system controls the actuators according to inputs and desired outputs of various systems.

For example, internal combustion engines combust an air and fuel mixture within cylinders to drive pistons, which produces drive torque. Air flow into the engine is regulated via a throttle. More specifically, the throttle adjusts throttle area, which increases or decreases air flow into the engine. As the throttle area increases, the air flow into the engine increases. A fuel control system adjusts the rate that fuel is injected to provide a desired air/fuel mixture to the cylinders and/or to achieve a desired torque output. Increasing the amount of air and fuel provided to the cylinders increases the torque output of the engine.

In spark-ignition engines, spark initiates combustion of an air/fuel mixture provided to the cylinders. In compression-ignition engines, compression in the cylinders combusts the air/fuel mixture provided to the cylinders. Spark timing and air flow may be the primary mechanisms for adjusting the torque output of spark-ignition engines, while fuel flow may be the primary mechanism for adjusting the torque output of compression-ignition engines.

SUMMARY

A control system includes a control module that receives a first request corresponding to a control value for at least one of a plurality of actuators, selectively receives a second request associated with a predicted future control value for at least one of the plurality of actuators, determines a target value for the actuator based on the first request if the second request was not received, and generates a reference signal indicating the second request if the second request was received. The reference signal indicates at least one of a predicted increase in the control value and a predicted decrease in the control value. A model predictive control module receives the reference signal and adjusts one of the plurality of actuators associated with the predicted future control value based on the reference signal.

An engine control system for a vehicle includes a torque requesting module that receives at least one torque request, selectively receives a predicted torque reserve request, determines an air torque request based on the at least one torque request if the predicted torque reserve request was not received, and generates a torque reference signal indicating the predicted torque reserve request if the predicted torque reserve request was received. The torque reference signal indicates at least one of a predicted torque request increase and a predicted torque request decrease. A model predictive control module receives the torque reference signal and adjusts a torque reserve based on the torque reference signal.

A method of operating an engine control system for a vehicle includes receiving at least one torque request, selectively receiving a predicted torque reserve request, determining an air torque request based on the at least one torque request if the predicted torque reserve request was not received, generating a torque reference signal indicating the predicted torque reserve request if the predicted torque reserve request was received, wherein the torque reference signal indicates at least one of a predicted torque request increase and a predicted torque request decrease, and adjusting a torque reserve based on the torque reference signal.

Further areas of applicability of the present disclosure will become apparent from the detailed description, the claims and the drawings. The detailed description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:

FIG. **1** is a functional block diagram of an example engine system according to the present disclosure;

FIG. **2** is a functional block diagram of an example engine control system according to the present disclosure;

FIG. **3** is a functional block diagram of an example air control module according to the present disclosure;

FIG. **4** is a functional block diagram of an example torque requesting module according to the present disclosure;

FIGS. **5**A and **5**B illustrate example timing loops for an artificial torque reference signal according to the present disclosure; and

FIG. **6** is a flow diagram of an example artificial torque reference method according to the present disclosure.

In the drawings, reference numbers may be reused to identify similar and/or identical elements.

DETAILED DESCRIPTION

A control module in a control system controls outputs of the system based on one or more inputs. The control module adjusts various actuators in the control system to achieve desired operating parameters based on the inputs. For example, the control module controls the actuators according to respective target values for each of the actuators to achieve the desired operating parameters. The actuators typically include some actuators that respond to control relatively slowly, and some actuators that respond to control relatively slowly. Accordingly, the control system may not be immediately responsive to inputs, and therefore desired outputs (i.e., desired operating parameters) may be delayed. In other words, the control system may not be able to immediately achieve the target values for each of the actuators.

A control module according to the present disclosure implements model predictive control to generate the target values. More specifically, the control module identifies possible sets of target values based on inputs to the control system. The control module determines predicted parameters for each of the possible sets based on the possible sets' target values and a mathematical model of the system. Further, the control module may selectively generate an artificial reference signal corresponding to predicted inputs. In this manner, the controls system can prepare to control actuators to target values based on the predicted inputs, and therefore more quickly respond when the actual inputs match the predicted inputs.

For example only, an engine control module (ECM) controls torque output of an engine. More specifically, the ECM controls actuators of the engine based on target values, respectively, based on a requested amount of torque. For example, the ECM controls intake and exhaust camshaft phasing based on target intake and exhaust phaser angles, a throttle valve based on a target throttle opening, an exhaust gas recirculation (EGR) valve based on a target EGR opening, and a wastegate of a turbocharger based on a target wastegate duty cycle.

The ECM could determine the target values individually using multiple single input single output (SISO) controllers, such as proportional integral derivative (PID) controllers. However, when multiple SISO controllers are used, the target values may be set to maintain system stability at the expense of possible fuel consumption decreases. Additionally, calibration and design of the individual SISO controllers may be costly and time consuming.

An example ECM that implements the artificial reference signal of the present disclosure generates the target values using model predictive control (MPC) as described above, and selectively uses the artificial torque reference signal to allow for torque reserve management. More specifically, the ECM identifies possible sets of target values based on an engine torque request and/or the artificial torque reference signal. The ECM determines predicted parameters for each of the possible sets based on the possible sets' target values and a mathematical model of the engine. For example, the ECM determines a predicted engine output torque and a predicted air per cylinder (APC) for each of the possible sets of target values. The ECM may also determine one or more other predicted parameters for each possible set of target values.

The ECM may determine a cost associated with use of each of the possible sets. For example, the cost of a possible set that is predicted to more closely track an engine torque request may be lower than other possible sets that are not expected to track the engine torque request as closely. The ECM may select the possible set that has the lowest cost and that satisfies various constraints (e.g. to minimize APC) for use to control the actuators. In various implementations, instead of or in addition to identifying possible sets of target values and determining the cost of each of the sets, the ECM may generate a surface representing the cost of possible sets of target values. The ECM may then identify the possible set that has the lowest cost based on the slope of the cost surface.

Referring now to FIG. **1**, a functional block diagram of an example engine system **100** is presented. Although the engine system **100** is presented as an example implementation of the MPC and artificial reference signal, the principles of the present disclosure can be implemented in any control system associated with controlling the target values of one or more actuators using MPC to achieve desired operating parameters.

The engine system **100** includes an engine **102** that combusts an air/fuel mixture to produce drive torque for a vehicle based on driver input from a driver input module **104**. The engine **102** may be a gasoline spark ignition internal combustion engine.

Air is drawn into an intake manifold **110** through a throttle valve **112**. For example only, the throttle valve **112** may include a butterfly valve having a rotatable blade. An engine control module (ECM) **114** controls a throttle actuator module **116**, which regulates opening of the throttle valve **112** to control the amount of air drawn into the intake manifold **110**.

Air from the intake manifold **110** is drawn into cylinders of the engine **102**. While the engine **102** may include multiple cylinders, for illustration purposes a single representative cylinder **118** is shown. For example only, the engine **102** may include 2, 3, 4, 5, 6, 8, 10, and/or 12 cylinders. The ECM **114** may instruct a cylinder actuator module **120** to selectively deactivate some of the cylinders, which may improve fuel economy under certain engine operating conditions.

The engine **102** may operate using a four-stroke cycle. The four strokes, described below, may be referred to as the intake stroke, the compression stroke, the combustion stroke, and the exhaust stroke. During each revolution of a crankshaft (not shown), two of the four strokes occur within the cylinder **118**. Therefore, two crankshaft revolutions are necessary for the cylinder **118** to experience all four of the strokes.

During the intake stroke, air from the intake manifold **110** is drawn into the cylinder **118** through an intake valve **122**. The ECM **114** controls a fuel actuator module **124**, which regulates fuel injection to achieve a target air/fuel ratio. Fuel may be injected into the intake manifold **110** at a central location or at multiple locations, such as near the intake valve **122** of each of the cylinders. In various implementations (not shown), fuel may be injected directly into the cylinders or into mixing chambers associated with the cylinders. The fuel actuator module **124** may halt injection of fuel to cylinders that are deactivated.

The injected fuel mixes with air and creates an air/fuel mixture in the cylinder **118**. During the compression stroke, a piston (not shown) within the cylinder **118** compresses the air/fuel mixture. A spark actuator module **126** energizes a spark plug **128** in the cylinder **118** based on a signal from the ECM **114**, which ignites the air/fuel mixture. The timing of the spark may be specified relative to the time when the piston is at its topmost position, referred to as top dead center (TDC).

The spark actuator module **126** may be controlled by a timing signal specifying how far before or after TDC to generate the spark. Because piston position is directly related to crankshaft rotation, operation of the spark actuator module **126** may be synchronized with crankshaft angle. Generating spark may be referred to as a firing event. The spark actuator module **126** may have the ability to vary the timing of the spark for each firing event. The spark actuator module **126** may vary the spark timing for a next firing event when the spark timing is changed between a last firing event and the next firing event. The spark actuator module **126** may halt provision of spark to deactivated cylinders.

During the combustion stroke, the combustion of the air/fuel mixture drives the piston away from TDC, thereby driving the crankshaft. The combustion stroke may be defined as the time between the piston reaching TDC and the time at which the piston reaches bottom dead center (BDC). During the exhaust stroke, the piston begins moving away from BDC and expels the byproducts of combustion through an exhaust valve **130**. The byproducts of combustion are exhausted from the vehicle via an exhaust system **134**.

The intake valve **122** may be controlled by an intake camshaft **140**, while the exhaust valve **130** may be controlled by an exhaust camshaft **142**. In various implementations, multiple intake camshafts (including the intake camshaft **140**) may control multiple intake valves (including the intake valve **122**) for the cylinder **118** and/or may control the intake valves (including the intake valve **122**) of multiple banks of cylinders (including the cylinder **118**). Similarly, multiple exhaust camshafts (including the exhaust camshaft **142**) may control multiple exhaust valves for the cylinder **118** and/or may control exhaust valves (including the exhaust valve **130**) for multiple banks of cylinders (including the cylinder **118**). In various other implementations, the intake valve **122** and/or the exhaust valve **130** may be controlled by devices other than camshafts, such as camless valve actuators. The cylinder actuator module **120** may deactivate the cylinder **118** by disabling opening of the intake valve **122** and/or the exhaust valve **130**.

The time when the intake valve **122** is opened may be varied with respect to piston TDC by an intake cam phaser **148**. The time when the exhaust valve **130** is opened may be varied with respect to piston TDC by an exhaust cam phaser **150**. A phaser actuator module **158** may control the intake cam phaser **148** and the exhaust cam phaser **150** based on signals from the ECM **114**. When implemented, variable valve lift (not shown) may also be controlled by the phaser actuator module **158**.

The engine system **100** may include a turbocharger that includes a hot turbine **160-1** that is powered by hot exhaust gases flowing through the exhaust system **134**. The turbocharger also includes a cold air compressor **160-2** that is driven by the turbine **160-1**. The compressor **160-2** compresses air leading into the throttle valve **112**. In various implementations, a supercharger (not shown), driven by the crankshaft, may compress air from the throttle valve **112** and deliver the compressed air to the intake manifold **110**.

A wastegate **162** may allow exhaust to bypass the turbine **160-1**, thereby reducing the boost (the amount of intake air compression) provided by the turbocharger. A boost actuator module **164** may control the boost of the turbocharger by controlling opening of the wastegate **162**. In various implementations, two or more turbochargers may be implemented and may be controlled by the boost actuator module **164**.

An air cooler (not shown) may transfer heat from the compressed air charge to a cooling medium, such as engine coolant or air. An air cooler that cools the compressed air charge using engine coolant may be referred to as an intercooler. An air cooler that cools the compressed air charge using air may be referred to as a charge air cooler. The compressed air charge may receive heat, for example, via compression and/or from components of the exhaust system **134**. Although shown separated for purposes of illustration, the turbine **160-1** and the compressor **160-2** may be attached to each other, placing intake air in close proximity to hot exhaust.

The engine system **100** may include an exhaust gas recirculation (EGR) valve **170**, which selectively redirects exhaust gas back to the intake manifold **110**. The EGR valve **170** may be located upstream of the turbocharger's turbine **160-1**. The EGR valve **170** may be controlled by an EGR actuator module **172** based on signals from the ECM **114**.

A position of the crankshaft may be measured using a crankshaft position sensor **180**. A rotational speed of the crankshaft (an engine speed) may be determined based on the crankshaft position. A temperature of the engine coolant may be measured using an engine coolant temperature (ECT) sensor **182**. The ECT sensor **182** may be located within the engine **102** or at other locations where the coolant is circulated, such as a radiator (not shown).

A pressure within the intake manifold **110** may be measured using a manifold absolute pressure (MAP) sensor **184**. In various implementations, engine vacuum, which is the difference between ambient air pressure and the pressure within the intake manifold **110**, may be measured. A mass flow rate of air flowing into the intake manifold **110** may be measured using a mass air flow (MAF) sensor **186**. In various implementations, the MAF sensor **186** may be located in a housing that also includes the throttle valve **112**.

The throttle actuator module **116** may monitor the position of the throttle valve **112** using one or more throttle position sensors (TPS) **190**. An ambient temperature of air being drawn into the engine **102** may be measured using an intake air temperature (IAT) sensor **192**. The engine system **100** may also include one or more other sensors **193**, such as an ambient humidity sensor, one or more knock sensors, a compressor outlet pressure sensor and/or a throttle inlet pressure sensor, a wastegate position sensor, an EGR position sensor, and/or one or more other suitable sensors. The ECM **114** may use signals from the sensors to make control decisions for the engine system **100**.

The ECM **114** may communicate with a transmission control module **194** to coordinate shifting gears in a transmission (not shown). For example, the ECM **114** may reduce engine torque during a gear shift. The ECM **114** may communicate with a hybrid control module **196** to coordinate operation of the engine **102** and an electric motor **198**.

The electric motor **198** may also function as a generator, and may be used to produce electrical energy for use by vehicle electrical systems and/or for storage in a battery. In various implementations, various functions of the ECM **114**, the transmission control module **194**, and the hybrid control module **196** may be integrated into one or more modules.

Each system that varies an engine parameter may be referred to as an engine actuator. For example, the throttle actuator module **116** may adjust opening of the throttle valve **112** to achieve a target throttle opening area. The spark actuator module **126** controls the spark plugs to achieve a target spark timing relative to piston TDC. The fuel actuator module **124** controls the fuel injectors to achieve target fueling parameters. The phaser actuator module **158** may control the intake and exhaust cam phasers **148** and **150** to achieve target intake and exhaust cam phaser angles, respectively. The EGR actuator module **172** may control the EGR valve **170** to achieve a target EGR opening area. The boost actuator module **164** controls the wastegate **162** to achieve a target wastegate opening area. The cylinder actuator module **120** controls cylinder deactivation to achieve a target number of activated or deactivated cylinders.

While the generation of target values using MPC can be implemented to control any of the above actuators (or actuators of any suitable control system), the implementation of the MPC systems and methods according to the principles of the present disclosure will be described with respect to the ECM **114** for example only. The ECM **114** generates the target values for the engine actuators to cause the engine **102** to generate a target engine output torque. The ECM **114** generates the target values for the engine actuators using model predictive control, as discussed further below.

Referring now to FIG. **2**, a functional block diagram of an example engine control system is presented. An example implementation of the ECM **114** includes a driver torque module **202**, an axle torque arbitration module **204**, and a propulsion torque arbitration module **206**. The ECM **114** may include a hybrid optimization module **208**. The ECM **114** also includes a reserves/loads module **220**, a torque requesting module **224**, an air control module **228**, a spark control module **232**, a cylinder control module **236**, and a fuel control module **240**.

The driver torque module **202** may determine a driver torque request **254** based on a driver input **255** from the driver input module **104**. The driver input **255** may be based on, for example, a position of an accelerator pedal and a position of a brake pedal. The driver input **255** may also be based on cruise control, which may be an adaptive cruise control system that varies vehicle speed to maintain a predetermined following distance. The driver torque module **202** may store one or more mappings of accelerator pedal position to target torque and may determine the driver torque request **254** based on a selected one of the mappings.

An axle torque arbitration module **204** arbitrates between the driver torque request **254** and other axle torque requests **256**. Axle torque (torque at the wheels) may be produced by various sources including an engine and/or an electric motor. For example, the axle torque requests **256** may include a torque reduction requested by a traction control system when positive wheel slip is detected. Positive wheel slip occurs when axle torque overcomes friction between the wheels and the road surface, and the wheels begin to slip against the road surface. The axle torque requests **256** may also include a torque increase request to counteract negative wheel slip, where a tire of the vehicle slips in the other direction with respect to the road surface because the axle torque is negative.

The axle torque requests **256** may also include brake management requests and vehicle over-speed torque requests. Brake management requests may reduce axle torque to ensure that the axle torque does not exceed the ability of the brakes to hold the vehicle when the vehicle is stopped. Vehicle overspeed torque requests may reduce the axle torque to prevent the vehicle from exceeding a predetermined speed. The axle torque requests **256** may also be generated by vehicle stability control systems.

The axle torque arbitration module **204** outputs a predicted torque request **257** and an immediate torque request **258** based on the results of arbitrating between the received torque requests **254** and **256**. As described below, the predicted and immediate torque requests **257** and **258** from the axle torque arbitration module **204** may selectively be adjusted by other modules of the ECM **114** before being used to control the engine actuators.

In general terms, the immediate torque request **258** may be an amount of currently desired axle torque, while the predicted torque request **257** may be an amount of axle torque that may be needed on short notice. The ECM **114** controls the engine system **100** to produce an axle torque equal to the immediate torque request **258**. However, different combinations of target values may result in the same axle torque. The ECM **114** may therefore adjust the target values to enable a faster transition to the predicted torque request **257**, while still maintaining the axle torque at the immediate torque request **258**.

In various implementations, the predicted torque request **257** may be set based on the driver torque request **254**. The immediate torque request **258** may be set to less than the predicted torque request **257** under some circumstances, such as when the driver torque request **254** is causing wheel slip on an icy surface. In such a case, a traction control system (not shown) may request a reduction via the immediate torque request **258**, and the ECM **114** reduces the engine torque output to the immediate torque request **258**. However, the ECM **114** performs the reduction so the engine system **100** can quickly resume producing the predicted torque request **257** once the wheel slip stops.

In general terms, the difference between the immediate torque request **258** and the (generally higher) predicted torque request **257** can be referred to as a torque reserve. The torque reserve may represent the amount of additional torque (above the immediate torque request **258**) that the engine system **100** can begin to produce with minimal delay. Fast engine actuators are used to increase or decrease current axle torque with minimal delay. Fast engine actuators are defined in contrast with slow engine actuators.

In general terms, fast engine actuators can change the axle torque more quickly than slow engine actuators. Slow actuators may respond more slowly to changes in their respective target values than fast actuators do. For example, a slow actuator may include mechanical components that require time to move from one position to another in response to a change in target value. A slow actuator may also be characterized by the amount of time it takes for the axle torque to begin to change once the slow actuator begins to implement the changed target value. Generally, this amount of time will be longer for slow actuators than for fast actuators. In addition, even after beginning to change, the axle torque may take longer to fully respond to a change in a slow actuator.

For example only, the spark actuator module **126** may be a fast actuator. Spark-ignition engines may combust fuels including, for example, gasoline and ethanol, by applying a spark. By way of contrast, the throttle actuator module **116** may be a slow actuator.

For example, as described above, the spark actuator module **126** can vary the spark timing for a next firing event when the spark timing is changed between a last firing event and the next firing event. By way of contrast, changes in throttle opening take longer to affect engine output torque. The throttle actuator module **116** changes the throttle opening by adjusting the angle of the blade of the throttle valve **112**. Therefore, when the target value for opening of the throttle valve **112** is changed, there is a mechanical delay as the throttle valve **112** moves from its previous position to a new position in response to the change. In addition, air flow changes based on the throttle opening are subject to air transport delays in the intake manifold **110**. Further, increased air flow in the intake manifold **110** is not realized as an increase in engine output torque until the cylinder **118** receives additional air in the next intake stroke, compresses the additional air, and commences the combustion stroke.

Using these actuators as an example, a torque reserve can be created by setting the throttle opening to a value that would allow the engine **102** to produce the predicted torque request **257**. Meanwhile, the spark timing can be set based on the immediate torque request **258**, which is less than the predicted torque request **257**. Although the throttle opening generates enough air flow for the engine **102** to produce the predicted torque request **257**, the spark timing is retarded (which reduces torque) based on the immediate torque request **258**. The engine output torque will therefore be equal to the immediate torque request **258**.

When additional torque is needed, the spark timing can be set based on the predicted torque request **257** or a torque between the predicted and immediate torque requests **257** and

258. By the following firing event, the spark actuator module 126 may return the spark timing to an optimum value, which allows the engine 102 to produce the full engine output torque achievable with the air flow already present. The engine output torque may therefore be quickly increased to the predicted torque request 257 without experiencing delays from changing the throttle opening.

The axle torque arbitration module 204 may output the predicted torque request 257 and the immediate torque request 258 to a propulsion torque arbitration module 206. In various implementations, the axle torque arbitration module 204 may output the predicted and immediate torque requests 257 and 258 to the hybrid optimization module 208.

The hybrid optimization module 208 may determine how much torque should be produced by the engine 102 and how much torque should be produced by the electric motor 198. The hybrid optimization module 208 then outputs modified predicted and immediate torque requests 259 and 260, respectively, to the propulsion torque arbitration module 206. In various implementations, the hybrid optimization module 208 may be implemented in the hybrid control module 196.

The predicted and immediate torque requests received by the propulsion torque arbitration module 206 are converted from an axle torque domain (torque at the wheels) into a propulsion torque domain (torque at the crankshaft). This conversion may occur before, after, as part of, or in place of the hybrid optimization module 208.

The propulsion torque arbitration module 206 arbitrates between propulsion torque requests 290, including the converted predicted and immediate torque requests. The propulsion torque arbitration module 206 generates an arbitrated predicted torque request 261 and an arbitrated immediate torque request 262. The arbitrated torque requests 261 and 262 may be generated by selecting a winning request from among received torque requests. Alternatively or additionally, the arbitrated torque requests may be generated by modifying one of the received requests based on another one or more of the received torque requests.

For example, the propulsion torque requests 290 may include torque reductions for engine over-speed protection, torque increases for stall prevention, and torque reductions requested by the transmission control module 194 to accommodate gear shifts. The propulsion torque requests 290 may also result from clutch fuel cutoff, which reduces the engine output torque when the driver depresses the clutch pedal in a manual transmission vehicle to prevent a flare in engine speed.

The propulsion torque requests 290 may also include an engine shutoff request, which may be initiated when a critical fault is detected. For example only, critical faults may include detection of vehicle theft, a stuck starter motor, electronic throttle control problems, and unexpected torque increases. In various implementations, when an engine shutoff request is present, arbitration selects the engine shutoff request as the winning request. When the engine shutoff request is present, the propulsion torque arbitration module 206 may output zero as the arbitrated predicted and immediate torque requests 261 and 262.

In various implementations, an engine shutoff request may simply shut down the engine 102 separately from the arbitration process. The propulsion torque arbitration module 206 may still receive the engine shutoff request so that, for example, appropriate data can be fed back to other torque requestors. For example, all other torque requestors may be informed that they have lost arbitration.

The reserves/loads module 220 receives the arbitrated predicted and immediate torque requests 261 and 262. The reserves/loads module 220 may adjust the arbitrated predicted and immediate torque requests 261 and 262 to create a torque reserve and/or to compensate for one or more loads. The reserves/loads module 220 then outputs adjusted predicted and immediate torque requests 263 and 264 to the torque requesting module 224.

For example only, a catalyst light-off process or a cold start emissions reduction process may require retarded spark timing. The reserves/loads module 220 may therefore increase the adjusted predicted torque request 263 above the adjusted immediate torque request 264 to create retarded spark for the cold start emissions reduction process. In another example, the air/fuel ratio of the engine and/or the mass air flow may be directly varied, such as by diagnostic intrusive equivalence ratio testing and/or new engine purging. Before beginning these processes, a torque reserve may be created or increased to quickly offset decreases in engine output torque that result from leaning the air/fuel mixture during these processes.

The reserves/loads module 220 may also create or increase a torque reserve in anticipation of a future load, such as power steering pump operation or engagement of an air conditioning (A/C) compressor clutch. The reserve for engagement of the A/C compressor clutch may be created when the driver first requests air conditioning. The reserves/loads module 220 may increase the adjusted predicted torque request 263 while leaving the adjusted immediate torque request 264 unchanged to produce the torque reserve. Then, when the A/C compressor clutch engages, the reserves/loads module 220 may increase the adjusted immediate torque request 264 by the estimated load of the A/C compressor clutch.

The torque requesting module 224 receives the adjusted predicted and immediate torque requests 263 and 264. The torque requesting module 224 determines how the adjusted predicted and immediate torque requests 263 and 264 will be achieved. The torque requesting module 224 may be engine type specific. For example, the torque requesting module 224 may be implemented differently or use different control schemes for spark-ignition engines versus compression-ignition engines.

In various implementations, the torque requesting module 224 may define a boundary between modules that are common across all engine types and modules that are engine type specific. For example, engine types may include spark-ignition and compression-ignition. Modules prior to the torque requesting module 224, such as the propulsion torque arbitration module 206, may be common across engine types, while the torque requesting module 224 and subsequent modules may be engine type specific.

The torque requesting module 224 determines an air torque request 265 based on the adjusted predicted and immediate torque requests 263 and 264. The air torque request 265 may be a brake torque. Brake torque may refer to torque at the crankshaft under the current operating conditions.

Target values for airflow controlling engine actuators are determined based on the air torque request 265. More specifically, based on the air torque request 265, the air control module 228 determines a target wastegate opening area 266, a target throttle opening area 267, a target EGR opening area 268, a target intake cam phaser angle 269, and a target exhaust cam phaser angle 270. The air control module 228 determines the target wastegate opening area 266, the target throttle opening area 267, the target EGR opening area 268, the target intake cam phaser angle 269, and the target exhaust cam phaser angle 270 using model predictive control, as discussed further below.

The boost actuator module 164 controls the wastegate 162 to achieve the target wastegate opening area 266. For example, a first conversion module **272** may convert the target wastegate opening area **266** into a target duty cycle **274** to be applied to the wastegate **162**, and the boost actuator module **164** may apply a signal to the wastegate **162** based on the target duty cycle **274**. In various implementations, the first conversion module **272** may convert the target wastegate opening area **266** into a target wastegate position (not shown), and convert the target wastegate position into the target duty cycle **274**.

The throttle actuator module **116** controls the throttle valve **112** to achieve the target throttle opening area **267**. For example, a second conversion module **276** may convert the target throttle opening area **267** into a target duty cycle **278** to be applied to the throttle valve **112**, and the throttle actuator module **116** may apply a signal to the throttle valve **112** based on the target duty cycle **278**. In various implementations, the second conversion module **276** may convert the target throttle opening area **267** into a target throttle position (not shown), and convert the target throttle position into the target duty cycle **278**.

The EGR actuator module **172** controls the EGR valve **170** to achieve the target EGR opening area **268**. For example, a third conversion module **280** may convert the target EGR opening area **268** into a target duty cycle **282** to be applied to the EGR valve **170**, and the EGR actuator module **172** may apply a signal to the EGR valve **170** based on the target duty cycle **282**. In various implementations, the third conversion module **280** may convert the target EGR opening area **268** into a target EGR position (not shown), and convert the target EGR position into the target duty cycle **282**.

The phaser actuator module **158** controls the intake cam phaser **148** to achieve the target intake cam phaser angle **269**. The phaser actuator module **158** also controls the exhaust cam phaser **150** to achieve the target exhaust cam phaser angle **270**. In various implementations, a fourth conversion module (not shown) may be included and may convert the target intake and exhaust cam phaser angles into target intake and exhaust duty cycles, respectively. The phaser actuator module **158** may apply the target intake and exhaust duty cycles to the intake and exhaust cam phasers **148** and **150**, respectively. In various implementations, the air control module **228** may determine a target overlap factor and a target effective displacement, and the phaser actuator module **158** may control the intake and exhaust cam phasers **148** and **150** to achieve the target overlap factor and the target effective displacement.

The torque requesting module **224** may also generate a spark torque request **283**, a cylinder shut-off torque request **284**, and a fuel torque request **285** based on the predicted and immediate torque requests **263** and **264**. The spark control module **232** may determine how much to retard the spark timing (which reduces engine output torque) from an optimum spark timing based on the spark torque request **283**. For example only, a torque relationship may be inverted to solve for a target spark timing **286**. For a given torque request (T_{Req}), the target spark timing (S_T) **286** may be determined based on:

$$S_T=f^{-1}(T_{Req},\mathrm{APC},I,E,\mathrm{AF},\mathrm{OT},\#), \quad (1)$$

where APC is an APC, I is an intake valve phasing value, E is an exhaust valve phasing value, AF is an air/fuel ratio, OT is an oil temperature, and # is a number of activated cylinders. This relationship may be embodied as an equation and/or as a lookup table. The air/fuel ratio (AF) may be the actual air/fuel ratio, as reported by the fuel control module **240**.

When the spark timing is set to the optimum spark timing, the resulting torque may be as close to a minimum spark advance for best torque (MBT) as possible. MBT corresponds to a maximum engine output torque that is generated for a given air flow as spark timing is advanced, while using fuel having an octane rating greater than a predetermined octane rating and using stoichiometric fueling. The spark timing at which this maximum torque occurs is referred to as an MBT spark timing. The optimum spark timing may differ slightly from MBT spark timing because of, for example, fuel quality (such as when lower octane fuel is used) and environmental factors, such as ambient humidity and temperature. The engine output torque at the optimum spark timing may therefore be less than MBT. For example only, a table of optimum spark timings corresponding to different engine operating conditions may be determined during a calibration phase of vehicle design, and the optimum value is determined from the table based on current engine operating conditions.

The cylinder shut-off torque request **284** may be used by the cylinder control module **236** to determine a target number of cylinders to deactivate **287**. In various implementations, a target number of cylinders to activate may be used. The cylinder actuator module **120** selectively activates and deactivates the valves of cylinders based on the target number **287**.

The cylinder control module **236** may also instruct the fuel control module **240** to stop providing fuel for deactivated cylinders and may instruct the spark control module **232** to stop providing spark for deactivated cylinders. The spark control module **232** may stop providing spark to a cylinder once an fuel/air mixture that is already present in the cylinder has been combusted.

The fuel control module **240** may vary the amount of fuel provided to each cylinder based on the fuel torque request **285**. More specifically, the fuel control module **240** may generate target fueling parameters **288** based on the fuel torque request **285**. The target fueling parameters **288** may include, for example, target mass of fuel, target injection starting timing, and target number of fuel injections.

During normal operation, the fuel control module **240** may operate in an air lead mode in which the fuel control module **240** attempts to maintain a stoichiometric air/fuel ratio by controlling fueling based on air flow. For example, the fuel control module **240** may determine a target fuel mass that will yield stoichiometric combustion when combined with a present mass of air per cylinder (APC).

The torque requesting module **224** selectively outputs an artificial torque reference signal **292** according to the present disclosure instead of the air torque request **265**. The torque reference signal **292** may correspond to a predicted load request and may be based on predicted torque reserve/load requests **294**, including, but not limited to, the reserve/load requests provided to the reserves/loads module **220**. For example, the predicted reserve/load requests **294** may be based on indications of future torque request changes received from the transmission control module **194**, air conditioning requests, or any other requests requiring a future change in torque. If the torque requesting module **224** determines that one or more of the predicted reserve/load requests **294** will require an increased or decreased amount of reserve torque, the torque requesting module **224** may output the artificial torque reference signal **292** instead of the air torque request **265**. In this manner, the air control module **228** controls one or more of the target values **266**-**270** according to the artificial torque reference signal to be able to more quickly meet torque reserve demands when the air torque request **265** subsequently increases/decreases to match the artificial torque reference signal **292**.

FIG. **3** is a functional block diagram of an example implementation of the air control module **228**. Referring now to FIGS. **2** and **3**, as discussed above, the air torque request **265** may be a brake torque. A torque conversion module **304** converts the air torque request **265** from brake torque into base torque. The torque request resulting from conversion into base torque will be referred to as a base air torque request **308**. Alternatively, the torque conversion module **304** receives the artificial torque reference signal **292** and converts the artificial torque reference signal **292** into the base air torque request **308**.

Base torques may refer to torque at the crankshaft made during operation of the engine **102** on a dynamometer while the engine **102** is warm and no torque loads are imposed on the engine **102** by accessories, such as an alternator and the A/C compressor. The torque conversion module **304** may convert the air torque request **265** or the artificial torque reference signal **292** into the base air torque request **308**, for example, using a mapping or a function that relates brake torques to base torques. In various implementations, the torque conversion module **304** may convert the air torque request **265** or the artificial torque reference signal **292** into another suitable type of torque, such as an indicated torque. An indicated torque may refer to a torque at the crankshaft attributable to work produced via combustion within the cylinders.

An MPC module **312** generates the target values **266-270** using a MPC (Model Predictive Control) scheme. The MPC module **312** may be a single module or may comprise multiple modules. For example, the MPC module **312** may include a sequence determination module **316**. The sequence determination module **316** determines possible sequences of the target values **266-270** that could be used together during N future control loops.

A prediction module **323** determines predicted responses of the engine **102** to the possible sequences of the target values **266-270**, respectively, based on a (mathematical) model **324** of the engine **102**, exogenous inputs **328**, and feedback inputs **330**. More specifically, based on a possible sequence of the target values **266-270**, the exogenous inputs **328**, and the feedback inputs **330**, using the model **324**, the prediction module **323** generates a sequence of predicted torques of the engine **102** for the N control loops, a sequence of predicted APCs for the N control loops, a sequence of predicted amounts of external dilution for the N control loops, a sequence of predicted amounts of residual dilution for the N control loops, a sequence of predicted combustion phasing values for the N control loops, and a sequence of predicted combustion quality values for the N control loops.

The model **324** may be, for example, a function or a mapping calibrated based on characteristics of the engine **102**. Dilution may refer to an amount of exhaust from a prior combustion event trapped within a cylinder for a combustion event. External dilution may refer to exhaust provided for a combustion event via the EGR valve **170**. Residual dilution (also referred to as internal dilution) may refer to exhaust that remains in a cylinder and/or exhaust that is pushed back into the cylinder following the exhaust stroke of a combustion cycle.

Combustion phasing may refer to a crankshaft position where a predetermined amount of fuel injected is combusted within a cylinder relative to a predetermined crankshaft position for combustion of the predetermined amount of injected fuel. For example, combustion phasing may be expressed in terms of CA50 relative to a predetermined CA50. CA50 may refer to a crankshaft angle (CA) where 50 percent of a mass of injected fuel has been combusted within a cylinder. The predetermined CA50 may correspond to a CA50 where a maximum amount of work is produced from the fuel injected and may be approximately 8.5-approximately 10 degrees after TDC (top dead center) in various implementations. While combustion phasing will be discussed in terms of CA50 values, another suitable parameter indicative of combustion phasing may be used. Additionally, while combustion quality will be discussed as coefficient of variation (COV) of indicated mean effective pressure (IMEP) values, another suitable parameter indicative of combustion quality may be used.

The exogenous inputs **328** may include parameters that are not directly affected by the throttle valve **112**, the EGR valve **170**, the turbocharger, the intake cam phaser **148**, and the exhaust cam phaser **150**. For example, the exogenous inputs **328** may include engine speed, turbocharger inlet air pressure, IAT, and/or one or more other parameters. The feedback inputs **330** may include, for example, an estimated torque output of the engine **102**, an exhaust pressure downstream of the turbine **160-1** of the turbocharger, the IAT, an APC of the engine **102**, an estimated residual dilution, an estimated external dilution, and/or one or more other suitable parameters. The feedback inputs **330** may be measured using sensors (e.g., the IAT) and/or estimated based on one or more other parameters.

Each of the possible sequences identified by the sequence determination module **316** includes one sequence of N values for each of the target values **266-270**. In other words, each possible sequence includes a sequence of N values for the target wastegate opening area **266**, a sequence of N values for the target throttle opening area **267**, a sequence of N values for the target EGR opening area **268**, a sequence of N values for the target intake cam phaser angle **269**, and a sequence of N values for the target exhaust cam phaser angle **270**. Each of the N values are for a corresponding one of the N future control loops. N is an integer greater than or equal to one.

A cost module **332** determines a cost value for each of the possible sequences of the target values **266-270** based on the predicted parameters determined for a possible sequence and output reference values **356**. An example cost determination is discussed further below.

A selection module **344** selects one of the possible sequences of the target values **266-270** based on the costs of the possible sequences, respectively. For example, the selection module **344** may select the one of the possible sequences having the lowest cost while satisfying actuator constraints **348** and output constraints **352**.

In various implementations, satisfaction of the actuator constraints **348** and the output constraints may be considered in the cost determination. In other words, the cost module **332** may determine the cost values further based on the actuator constraints **348** and the output constraints **352**. As discussed further below, based on how the cost values are determined, the selection module **344** will select the one of the possible sequences that best achieves the base air torque request **208** while minimizing the APC, subject to the actuator constraints **348** and the output constraints **352**.

The selection module **344** may set the target values **266-270** to the first ones of the N values of the selected possible sequence, respectively. In other words, the selection module **344** may set the target wastegate opening area **266** to the first one of the N values in the sequence of N values for the target wastegate opening area **266**, set the target throttle opening area **267** to the first one of the N values in the sequence of N values for the target throttle opening area **267**, set the target EGR opening area **268** to the first one of the N values in the sequence of N values for the target EGR opening area **268**, set the target intake cam phaser angle **269** to the first one of the N values in the sequence of N values for the target intake cam phaser angle **269**, and set the target exhaust cam phaser angle

270 to the first one of the N values in the sequence of N values for the target exhaust cam phaser angle **270**.

During a next control loop, the MPC module **312** identifies possible sequences, generates the predicted parameters for the possible sequences, determines the cost of each of the possible sequences, selects of one of the possible sequences, and sets of the target values **266-270** to the first set of the target values **266-270** in the selected possible sequence. This process continues for each control loop.

An actuator constraint module **360** (see FIG. **2**) sets one of the actuator constraints **348** for each of the target values **266-270**. In other words, the actuator constraint module **360** sets an actuator constraint for the throttle valve **112**, an actuator constraint for the EGR valve **170**, an actuator constraint for the wastegate **162**, an actuator constraint for the intake cam phaser **148**, and an actuator constraint for the exhaust cam phaser **150**.

The actuator constraints **348** for each one of the target values **266-270** may include a maximum value for an associated target value and a minimum value for that target value. The actuator constraint module **360** may generally set the actuator constraints **348** to predetermined operational ranges for the associated actuators. More specifically, the actuator constraint module **360** may generally set the actuator constraints **348** to predetermined operational ranges for the throttle valve **112**, the EGR valve **170**, the wastegate **162**, the intake cam phaser **148**, and the exhaust cam phaser **150**, respectively.

However, the actuator constraint module **360** may selectively adjust one or more of the actuator constraints **348** under some circumstances. For example, the actuator constraint module **360** may adjust the actuator constraints for a given actuator to narrow the operational range for that engine actuator when a fault is diagnosed in that engine actuator. For another example only, the actuator constraint module **360** may adjust the actuator constraints such that the target value for a given actuator follows a predetermined schedule over time or changes by a predetermined amount, for example, for a fault diagnostic, such as a cam phaser fault diagnostic, a throttle diagnostic, an EGR diagnostic, etc. For a target value to follow a predetermined schedule over time or to change by a predetermined amount, the actuator constraint module **360** may set the minimum and maximum values to the same value. The minimum and maximum values being set to the same value may force the corresponding target value to be set to the same value as the minimum and maximum values. The actuator constraint module **360** may vary the same value to which the minimum and maximum values are set over time to cause the target value to follow a predetermined schedule.

An output constraint module **364** (see FIG. **2**) sets the output constraints **352** for the predicted torque output of the engine **102**, the predicted CA50, the predicted COV of IMEP, the predicted residual dilution, and the predicted external dilution. The output constraints **352** for each one of the predicted values may include a maximum value for an associated predicted parameter and a minimum value for that predicted parameter. For example, the output constraints **352** may include a minimum torque, a maximum torque, a minimum CA50 and a maximum CA50, a minimum COV of IMEP and a maximum COV of IMEP, a minimum residual dilution and a maximum residual dilution, and a minimum external dilution and a maximum external dilution.

The output constraint module **364** may generally set the output constraints **352** to predetermined ranges for the associated predicted parameters, respectively. However, the output constraint module **364** may vary one or more of the output constraints **352** under some circumstances. For example, the output constraint module **364** may retard the maximum CA50, such as when knock occurs within the engine **102**. For another example, the output constraint module **364** may increase the maximum COV of IMEP under low load conditions, such as during engine idling where the a higher COV of IMEP may be needed to achieve a given torque request.

A reference module **368** (see FIG. **2**) generates the reference values **356** for the target values **266-270**, respectively. The reference values **356** include a reference for each of the target values **266-270**. In other words, the reference values **356** include a reference wastegate opening area, a reference throttle opening area, a reference EGR opening area, a reference intake cam phaser angle, and a reference exhaust cam phaser angle.

The reference module **368** may determine the reference values **356**, for example, based on the air torque request **265**, the base air torque request **308**, and/or one or more other suitable parameters. The reference values **356** provide references for setting the target values **266-270**, respectively. The reference values **356** may be used to determine the cost values for possible sequences. The reference values **356** may also be used for one or more other reasons, such as by the sequence determination module **316** to determine possible sequences.

Instead of or in addition to generating sequences of possible target values and determining the cost of each of the sequences, the MPC module **312** may identify a sequence of possible target values having the lowest cost using convex optimization techniques. For example, the MPC module **312** may determine the target values **266-270** using a quadratic programming (QP) solver, such as a Dantzig QP solver. In another example, the MPC module **312** may generate a surface of cost values for the possible sequences of the target values **266-270** and, based on the slope of the cost surface, identify a set of possible target values having the lowest cost. The MPC module **312** may then test that set of possible target values to determine whether that set of possible target values will satisfy the actuator constraints **348** and the output constraints **352**. The MPC module **312** selects the set of possible target values having the lowest cost while satisfying the actuator constraints **348** and the output constraints **352**.

The cost module **332** may determine the cost for the possible sequences of the target values **266-270** based on relationships between: the predicted torque and the base air torque request **308**; the predicted APC and zero; the possible target values and the respective actuator constraints **348**; the other predicted parameters and the respective output constraints **352**; and the possible target values and the respective reference values **356**. The relationships may be weighted, for example, to control the effect that each of the relationships has on the cost.

For example only, the cost module **332** may determine the cost for a possible sequence of the target values **266-270** based on the equation:

$$\text{Cost}=\Sigma_{i=1}^{N} wT^{*}\|TP_i-\text{BATR}\|+wA^{*}\|\text{APCP}_i-0\|,$$

where Cost is the cost for the possible sequence of the target values **266-270**, TPi is the predicted torque of the engine **102** for an i-th one of the N control loops, BATR is the base air torque request **308**, and wT is a weighting value associated with the relationship between the predicted and reference engine torques. APCPi is a predicted APC for the i-th one of the N control loops and wA is a weighting value associated with the relationship between the predicted APC and zero.

The cost module **332** may determine the cost for a possible sequence of the target values **266-270** based on the following more detailed equation:

$$\mathrm{Cost}=\sum_{i=1}^{N}\rho\epsilon^2+wT^2*\|\mathrm{TP}_i-\mathrm{BATR}\|^2+wA^2*\|\mathrm{APCP}_i-0\|^2+wTV^2*\|\mathrm{PTTO}i-\mathrm{TORef}\|^2+wWG^2*\|\mathrm{PTWGO}i-\mathrm{EGORef}\|^2+w\mathrm{EGR}^2*\|\mathrm{PTEGRO}i-\mathrm{EGRORef}\|^2+wIP^2*\|\mathrm{PTICP}i-\mathrm{ICPRef}\|^2+wEP^2*\|\mathrm{PTECP}i-\mathrm{ECPRef}\|^2,$$

subject to the actuator constraints **348** and the output constraints **352**. Cost is the cost for the possible sequence of the target values **266-270**, TPi is the predicted torque of the engine **102** for an i-th one of the N control loops, BATR is the base air torque request **308**, and wT is a weighting value associated with the relationship between the predicted and reference engine torques. APCPi is a predicted APC for the i-th one of the N control loops and WA is a weighting value associated with the relationship between the predicted APC and zero.

PTTOi is a possible target throttle opening for the i-th one of the N control loops, TORef is the reference throttle opening, and wTV is a weighting value associated with the relationship between the possible target throttle openings and the reference throttle opening. PTWGOi is a possible target wastegate opening for the i-th one of the N control loops, WGORef is the reference wastegate opening, and wWG is a weighting value associated with the relationship between the possible target wastegate openings and the reference wastegate opening.

PTEGROi is a possible target EGR opening for the i-th one of the N control loops, EGRRef is the reference EGR opening, and wEGR is a weighting value associated with the relationship between the possible target EGR openings and the reference EGR opening. PTICi is a possible target intake cam phaser angle for the i-th one of the N control loops, ICPRef is the reference intake cam phaser angle, and wIP is a weighting value associated with the relationship between the possible target intake cam phaser angle and the reference intake cam phaser angle. PTECi is a possible target exhaust cam phaser angle for the i-th one of the N control loops, ECPRef is the reference exhaust cam phaser angle, and wEP is a weighting value associated with the relationship between the possible target exhaust cam phaser angle and the reference exhaust cam phaser angle.

ρ is a weighting value associated with satisfaction of the output constraints **352**. ϵ is a variable that the cost module **332** may set based on whether the output constraints **352** will be satisfied. For example, the cost module **332** may increase ϵ when a predicted parameter is greater than or less than the corresponding minimum or maximum value (e.g., by at least a predetermined amount). The cost module **332** may set ϵ to zero when all of the output constraints **352** are satisfied. ρ may be greater than the weighting value wT, the weighting value wA, and the other weighting values (wTV, wWG, wEGR, wIP, wEP) such that the cost determined for a possible sequence will be large if one or more of the output constraints **352** are not satisfied. This may help prevent selection of a possible sequence where one or more of the output constraints **352** are not satisfied.

The weighting value wT may be greater than the weighting value wA and the weighting values wTV, wWG, wEGR, wIP, and wEP. In this manner, the relationship between the relationship between the predicted engine torque and the base air torque request **308** have a larger effect on the cost and, therefore, the selection of one of the possible sequences as discussed further below. The cost increases as the difference between the predicted engine torque and the base air torque request **308** increases and vice versa.

The weighting value wA may be less than the weighting value wT and greater than the weighting values wTV, wWG, wEGR, wIP, and wEP. In this manner, the relationship between the predicted APC and zero has a large effect on the cost, but less than the relationship between the predicted engine torque and the base air torque request **308**. The cost increases as the difference between the predicted APC and zero increases and vice versa. While the example use of zero is shown and has been discussed, a predetermined minimum APC may be used in place of zero.

Determining the cost based on the difference between the predicted APC and zero therefore helps ensure that the APC will be minimized. Decreasing APC decreases fuel consumption as fueling is controlled based on the actual APC to achieve a target air/fuel mixture. As the selection module **344** may select the one of the possible sequences having the lowest cost, the selection module **344** may select the one of the possible sequences that best achieves the base air torque request **308** while minimizing the APC.

The weighting values wTV, wWG, wEGR, wIP, and wEP may be less than all of the other weighting values. In this manner, during steady-state operation, the target values **266-270** may settle near or at the reference values **356**, respectively. During transient operation, however, the MPC module **312** may adjust the target values **266-270** away from the reference values **356** in order to achieve the base air torque request **308**, while minimizing the APC and satisfying the actuator constraints **348** and the output constraints **352**.

In operation, the MPC module **312** may determine the cost values for the possible sequences. The MPC module **312** may then select the one of the possible sequences having the lowest cost. The MPC module **312** may next determine whether the selected possible sequence satisfies the actuator constraints **348**. If so, the possible sequence may be used. If not, the MPC module **312** determines, based on the selected possible sequence, a possible sequence that satisfies the actuator constraints **348** and that has the lowest cost. The MPC module **312** may use the possible sequence that satisfies the actuator constraints **348** and that has the lowest cost.

Referring now to FIG. **4**, an example torque requesting module **400** according to the present disclosure includes a torque request output module **404** and an artificial torque reference module **408**. The torque request output module **404** receives the predicted and immediate torque requests **263** and **264** and the predicted reserve/load requests **294** and selectively outputs one of the air torque request **265** and the artificial torque reference signal **292** accordingly. For example, if the torque requesting module **400** does not receive any of the predicted reserve/load requests **294** (and/or none of the predicted reserve/load requests **294** indicate a needed future change in torque reserve due to a transmission shift, air conditioning increase, etc.), then the torque request output module **404** may output the air torque request **265** based on the predicted and immediate torque requests **263** and **264**.

Conversely, if the torque requesting module **400** receives predicted reserve/load requests **294** indicating a future torque request/reserve change, then the torque request output module **404** instead outputs the artificial torque reference signal **292**. For example, the torque request output module **404** may calculate the artificial torque reference signal **292** based on the predicted and immediate torque requests **263** and **264** and the predicted reserve/load requests **294**.

Alternatively, the torque request output module **404** may retrieve a value for the artificial torque reference signal **292** from the artificial torque reference module **408**. For example, the artificial torque reference module **408** may calculate (e.g., model) the artificial torque reference signal **292** based on the predicted and immediate torque requests **263** and **264**, the predicted reserve/load requests **294**, types of the predicted reserve/load requests, etc., which may be provided to the artificial torque reference module **408** by the torque request output module **404**. In some implementations, the artificial torque reference module **408** may store a plurality of values for the artificial torque reference signal **292** indexed by the predicted and immediate torque requests **263** and **264** and the predicted reserve/load requests **294** (e.g., in a lookup table). The values for the artificial torque reference signal **292** may include offsets (e.g., positive or negative offsets to be added to or subtracted from a value calculated for the air torque request **265**.

Accordingly, the artificial torque reference signal **292** may correspond to a value calculated for the air torque request **265**, plus or minus an offset corresponding to one or more of the predicted reserve/load requests **294**. In this manner, the artificial torque reference signal **292** includes the air torque request **265** and any anticipated future changes to the air torque request **265** indicated by one or more of the predicted reserve/load requests **294**.

Referring now to FIGS. **5**A and **5**B, example timing loops **500-1** through **500-7** (referred to collectively as timing loops **500**) illustrate an artificial torque reference signals **504** (artificial torque reference signals **504-1** through **504-7**) provided to the model predictive control module **312** (e.g., via the torque conversion module **304** and the base air torque request **308**).

In each one of the timing loops **500**, the respective artificial torque reference signal **504** corresponds to a requested torque profile provided to the model predictive control module **312** at a given time (0, +1, +2, . . . , +6), and indicates predicted requested torque for one or more time steps **508** in the future. For example, for each of the timing loops **500**, “1” indicates a first time step in the future (e.g., 25 ms after the respective artificial torque reference signal **504** is provided to the model predictive control module **312**), “2” indicates a second time step in the future, “3” indicates a third time step in the future, etc.

For example, in the timing loop **500-1**, the signal **504-1** indicates an increase in predicted requested torque at the third time step 3. Accordingly, the model predictive control module **312** can begin to increase torque reserve **512** in anticipation of the increase in the predicted requested torque at the third time step 3 as indicated by the artificial torque reference signal **504-1**. Consequently, the torque reserve **512** will increase at the first time step 1, the second time step 2, and the third time step 3 until the torque reserve **512** is sufficient to compensate for the predicted requested torque in the third time step 3. However, an actual requested torque **516** is not changed at the first time step 1 or the second time step 2 because the model predictive control module **312** does not need to provide the increased torque until the third time step 3. In this manner, the model predictive control module **312** prepares for the increase in requested torque indicated by the artificial torque reference signal **504-1** at the third time step 3 by increasing the torque reserve **512** without affecting the actual requested torque **516**.

In the timing loops **500-2**, **500-3**, and **500-4**, the signals **504-2**, **504-3**, and **504-4**, respectively, again indicate an increase in predicted requested torque at the third time step 3. Accordingly, the torque reserve **512** continues to increase in anticipation of the predicted (i.e., scheduled) increase in requested torque indicated by the signal **504** at the third time step 3. The artificial torque reference signal **504** may be provided with the future increase indicated at the third time step 3 in the future until the torque reserve **512** is approximately sufficient to compensate for the increase (i.e., approximately equal to the additional torque required when the actual requested torque **512** increases to match the artificial torque reference signal **514**) as shown in the timing loop **500-4**.

In the timing loop **500-5**, the artificial torque reference signal **514-5** indicates the increase in predicted requested torque at the second time step 2. In the timing loop **500-6**, the artificial torque reference signal **514-6** indicates the increase in predicted requested torque at the first time step 1. Accordingly, the torque reserve **512** is maintained at a level sufficient to compensate for the increase in predicted requested torque. In the timing loop **500-7**, the actual requested torque **516** increases to match the artificial torque reference signal **514-7**. However, because the model predictive torque module **312** previously prepared for the increase, the torque reserve **512** is immediately available. As shown in the timing loop **500-7**, the torque reserve **512** is quickly depleted in response to the increase in actual requested torque **516**.

Although the predicted requested torque is shown in FIGS. **5**A and **5**B as an increase, the predicted requested torque may also correspond to a decrease in requested torque. Accordingly, the model predictive control module **312** can anticipate a decrease in requested torque (e.g., by decreasing torque reserve).

In this manner, a future torque request (i.e., as indicated by the predicted torque request) can be repeated a same number of time steps from the current time step in successive timing loops until the torque reserve **512** is sufficiently prepared to accommodate the future torque request. When the torque reserve **512** is sufficiently prepared, the actual torque request change is provided to the MPC module **312**.

Referring now to FIG. **6**, an example artificial torque reference method **600** begins at **604**. At **608**, the method **600** receives predicted and immediate torque requests. At **612**, the method **600** determines whether any predicted reserve/load requests were received. If true, the method **600** continues to **616**. If false, the method **600** continues to **620**. At **620**, the method **600** generates an air torque request based on the predicted and immediate torque requests. At **624**, the method **600** controls torque reserve based on the air torque request. The method **600** ends at **628**.

At **616**, the method **600** determines an artificial torque request signal based on the predicted and immediate torque requests, the predicted reserve request, and/or an air torque request. At **632**, the method **600** controls reserve torque based on the artificial torque reference signal.

The foregoing description is merely illustrative in nature and is in no way intended to limit the disclosure, its application, or uses. The broad teachings of the disclosure can be implemented in a variety of forms. Therefore, while this disclosure includes particular examples, the true scope of the disclosure should not be so limited since other modifications will become apparent upon a study of the drawings, the specification, and the following claims. As used herein, the phrase at least one of A, B, and C should be construed to mean a logical (A or B or C), using a non-exclusive logical OR. It should be understood that one or more steps within a method may be executed in different order (or concurrently) without altering the principles of the present disclosure.

In this application, including the definitions below, the term module may be replaced with the term circuit. The term module may refer to, be part of, or include an Application Specific Integrated Circuit (ASIC); a digital, analog, or mixed analog/digital discrete circuit; a digital, analog, or mixed analog/digital integrated circuit; a combinational logic circuit; a field programmable gate array (FPGA); a processor (shared, dedicated, or group) that executes code; memory (shared, dedicated, or group) that stores code executed by a processor; other suitable hardware components that provide the described functionality; or a combination of some or all of the above, such as in a system-on-chip.

The term code, as used above, may include software, firmware, and/or microcode, and may refer to programs, routines, functions, classes, and/or objects. The term shared processor encompasses a single processor that executes some or all code from multiple modules. The term group processor encompasses a processor that, in combination with additional processors, executes some or all code from one or more modules. The term shared memory encompasses a single memory that stores some or all code from multiple modules. The term group memory encompasses a memory that, in combination with additional memories, stores some or all code from one or more modules. The term memory may be a subset of the term computer-readable medium. The term computer-readable medium does not encompass transitory electrical and electromagnetic signals propagating through a medium, and may therefore be considered tangible and non-transitory. Non-limiting examples of a non-transitory tangible computer readable medium include nonvolatile memory, volatile memory, magnetic storage, and optical storage.

The apparatuses and methods described in this application may be partially or fully implemented by one or more computer programs executed by one or more processors. The computer programs include processor-executable instructions that are stored on at least one non-transitory tangible computer readable medium. The computer programs may also include and/or rely on stored data.

What is claimed is:

1. A control system, comprising:

a control module that
 receives a first request corresponding to a control value for at least one of a plurality of actuators,
 selectively receives a second request associated with a predicted future control value for at least one of the plurality of actuators,
 if the second request was not received, determines a target value for the actuator based on the first request, and
 if the second request was received, generates a reference signal representing the second request, wherein the reference signal indicates at least one of a predicted increase in the control value and a predicted decrease in the control value; and
a model predictive control module that receives the reference signal and adjusts one of the plurality of actuators associated with the predicted future control value based on the reference signal.

2. The control system of claim **1**, wherein the reference signal corresponds to the first request plus or minus an offset indicated by the second request.

3. The control system of claim **1**, wherein control module determines the reference signal based on the first request and the second request.

4. The control system of claim **1**, wherein the reference signal includes an increase at a second time subsequent to a first time that the reference signal is provided to the model predictive control module.

5. The control system of claim **4**, wherein the model predictive control module adjusts the one of the plurality of actuators associated with the predicted future control value prior to the second time.

6. An engine control system for a vehicle, the engine control system comprising:

a torque requesting module that
 receives at least one torque request and selectively receives a predicted torque reserve request,
 if the predicted torque reserve request was not received, determines an air torque request based on the at least one torque request, and
 if the predicted torque reserve request was received, generates a torque reference signal indicating the predicted torque reserve request, wherein the torque reference signal indicates at least one of a predicted torque request increase and a predicted torque request decrease; and
a model predictive control module that receives the torque reference signal and adjusts a torque reserve based on the torque reference signal.

7. The engine control system of claim **6**, wherein the torque reference signal corresponds to the air torque request plus or minus an offset indicated by the predicted torque reserve request.

8. The engine control system of claim **6**, wherein the torque requesting module determines the torque reference signal based on the at least one torque request and the predicted torque reserve request.

9. The engine control system of claim **6**, wherein the torque reference signal includes an increase at a second time subsequent to a first time that the torque reference signal is provided to the model predictive control module.

10. The engine control system of claim **9**, wherein the model predictive control module increases the torque reserve prior to the second time.

11. The engine control system of claim **10**, wherein the model predictive control module increases the torque reserve until the torque reserve is approximately equal to an amount of torque corresponding to the predicted torque reserve request.

12. The engine control system of claim **11**, wherein the torque reference signal includes the increase at a third time subsequent to the first time when the torque reserve is approximately equal to an amount of torque corresponding to the predicted torque reserve request, and wherein the third time is subsequent to the first time and prior to the second time.

13. A method of operating an engine control system for a vehicle, the method comprising:

receiving at least one torque request,
selectively receiving a predicted torque reserve request;
determining an air torque request based on the at least one torque request if the predicted torque reserve request was not received;
determining a torque reference signal indicating the predicted torque reserve request if the predicted torque reserve request was received, wherein the torque reference signal indicates at least one of a predicted torque request increase and a predicted torque request decrease; and
adjusting a torque reserve based on the torque reference signal.

14. The method of claim **13**, wherein the torque reference signal corresponds to the air torque request plus or minus an offset indicated by the predicted torque reserve request.

15. The method of claim **13**, further comprising determining the torque reference signal based on the at least one torque request and the predicted torque reserve request.

16. The method of claim **13**, wherein the torque reference signal includes an increase at a second time subsequent to a first time that the torque reference signal is determined.

17. The method of claim **16**, further comprising increasing the torque reserve prior to the second time.

18. The method of claim **17**, further comprising increasing the torque reserve until the torque reserve is approximately equal to an amount of torque corresponding to the predicted torque reserve request.

19. The method of claim **18**, wherein the torque reference signal includes the increase at a third time subsequent to the first time when the torque reserve is approximately equal to an amount of torque corresponding to the predicted torque reserve request, and wherein the third time is subsequent to the first time and prior to the second time.

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