SYSTEM AND METHOD FOR MANAGING THE PERIOD OF A CONTROL LOOP FOR CONTROLLING AN ENGINE USING MODEL PREDICTIVE CONTROL

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A system according to the present disclosure includes a model predictive control (MPC) module, an actuator module, and a remedial action module. The MPC module performs MPC tasks that include predicting operating parameters for a set of possible target values and determining a cost for the set of possible target values based on the predicted operating parameters. The MPC tasks also include selecting the set of possible target values from multiple sets of possible target values based on the cost and setting target values to the possible target values of the selected set. The actuator module controls an actuator of an engine based on at least one of the target values. The remedial action module selectively takes a remedial action based on at least one of an amount of time that elapses as the MPC tasks are performed and a number of iterations of the MPC tasks that are performed.

20 Claims, 6 Drawing Sheets
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FIG. 4
SYSTEM AND METHOD FOR MANAGING THE PERIOD OF A CONTROL LOOP FOR CONTROLLING AN ENGINE USING MODEL PREDICTIVE CONTROL

CROSS-REFERENCE TO RELATED APPLICATIONS


FIELD

The present disclosure relates to internal combustion engines, and more particularly, to systems and methods for managing the period of a control loop for controlling an engine using model predictive control.

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.

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.

Engine control systems have been developed to control engine output torque to achieve a desired torque. Traditional engine control systems, however, do not control the engine output torque as accurately as desired. Further, traditional engine control systems do not provide a rapid response to control signals or coordinate engine torque control among various devices that affect the engine output torque.

SUMMARY

A system according to the present disclosure includes a model predictive control (MPC) module, an actuator module, and a remedial action module. The MPC module performs MPC tasks that include predicting operating parameters for a set of possible target values and determining a cost for the set of possible target values based on the predicted operating parameters. The MPC tasks also include selecting the set of possible target values from multiple sets of possible target values based on the cost and setting target values to the possible target values of the selected set. The actuator module controls an actuator of an engine based on at least one of the target values. The remedial action module selectively takes a remedial action based on at least one of an amount of time that elapses as the MPC tasks are performed and a number of iterations of the MPC tasks that are performed.

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 flowchart depicting an example method of controlling a throttle valve, intake and exhaust valve phasing, a wastegate, and an exhaust gas recirculation (EGR) valve using model predictive control according to the present disclosure;
FIG. 5 is a flowchart depicting an example method of managing a period of a control loop executed by a model predictive control module according to the present disclosure; and
FIG. 6 is a graph further illustrating the example method of FIG. 5.

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

DETAILED DESCRIPTION

An engine control module (ECM) controls torque output of an engine. More specifically, the ECM controls actuators of the engine based on target values 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 decreases in fuel consumption. Additionally, calibration and design of the individual SISO controllers may be costly and time consuming.

The ECM of the present disclosure generates the target values using a model predictive control (MPC) module. The MPC module identifies possible sets of target values based
on an engine torque request. The MPC module determines predicted parameters for each of the possible sets based on the possible sets' target values and a mathematical model of the engine.

The MPC module may also determine a cost associated with each of the possible sets. The cost determined for a possible set may increase as differences between the target values of the possible set and reference values increase and vice versa. The MPC module may select the possible set that has the lowest cost. Instead of or in addition to identifying possible sets of target values and determining the cost of each of the sets, the MPC module may generate a surface representing the cost of possible sets of target values. The MPC module may then identify the possible set that has the lowest cost based on the slope of the cost surface.

The MPC module may determine whether the predicted parameters of the selected set satisfy constraints. If not, the MPC module may set the target values based on the selected set. Otherwise, the MPC module may select the possible set having the next lowest cost and test that set for satisfaction of the constraints. The process of selecting a set and testing the set for satisfaction of the constraints may be referred to as an iteration. Multiple iterations may be performed during each control loop.

The ECM of the present disclosure may monitor the time that elapses as the MPC module performs iterations and take one or more remedial actions if the iteration time is greater than a threshold. In some instances, the period required to perform a single iteration may be known, in which case the ECM may monitor the number of iterations that are performed and multiply the number of iterations by the predetermined iteration period to obtain the iteration time. Iterations started during the current loop may be referred to as the current iterations and the time that elapses as the MPC module performs the current iterations may be referred to as the current iteration time. If the current iteration time extends into the period allotted for the next loop, the ECM may instruct the MPC module to set the target values for the current loop to the target values set for the last loop and to refrain from restarting iterations in the next loop.

In this manner, the ECM allows the MPC to complete the current iterations during the next loop. Allowing the MPC module to complete the current iterations during the next loop may reduce the amount of time required to complete iterations started during subsequent control loops. In addition, the loop rate of the MPC module may be decreased relative to a worst-case loop rate for the longest expected iteration time.

If the current iteration time exceeds the period allotted for the next control loop, the solution sought by the MPC module may be infeasible or there may be another error in the MPC module. Thus, the ECM may diagnose a fault in the MPC module. The ECM may also reset and reinitialize the MPC module, activate a service indicator such as a malfunction indicator lamp, and/or limit the torque output of the engine.

Referring now to FIG. 1, a functional block diagram of an example engine system 100 is presented. 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 separately 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 also may 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.

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 (MPC), as discussed further below. The ECM 114 also monitors the time elapsed while generating the target values and takes a remedial action and/or diagnoses a fault when the elapsed time is greater than a predetermined period. The ECM 114 may set a diagnostic trouble code (DTC) and/or activate a service indicator 199 when a fault is diagnosed. The service indicator 199 indicates that service is required using a visual message (e.g., text), an audible message (e.g., chime), and/or a tactile message (e.g., vibration).

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. The other axle torque requests 256 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 over-speed 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 260, 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 259 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 259 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 259 may also include an engine shutdown 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 shutdown request is present, arbitration selects the engine shutdown request as the winning request. When the engine shutdown 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 shutdown request may simply shut down the engine 102 separately from the arbitration process. The propulsion torque arbitration module 206 may still receive the engine shutdown 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
When the spark timing is set to the optimum spark timing, the resulting torque may be as close to a maximum best torque (MBT) as possible. MBT refers to the 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).

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.

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 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 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 MPC (Model Predictive Control). The MPC module 312 may be a single module or 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. 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 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 is for a corresponding one of the N future control loops. N is an integer greater than or equal to one.

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, the 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. While an example of generating predicted torque, predicted APC, predicted external dilution, predicted residual dilution, predicted combustion phasing, and predicted combustion quality is described, the predicted parameters may include one or more other predicted engine operating parameters.

The model 324 may include, 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 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. Residual dilution may also be referred to as internal dilution.

Combustion phasing may refer to a crankshaft position where a predetermined amount of fuel is injected into a crankshaft position where a predetermined amount of fuel is injected 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, 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.

The 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 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 308 while minimizing fuel consumption, 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 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 the actuator constraints 348 for each of the target values 266-270. In other words, the actuator constraint module 360 sets actuator constraints for the throttle valve 112, actuator constraints for the EGR valve 170, actuator constraints for...
the wastegate 162, actuator constraints for the intake cam phaser 148, and actuator constraints 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. In addition, the actuator constraints 248 may include a rate of change constraint for an associated 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 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 and/or the base air torque request 308. 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, as discussed further below. 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 sequence of possible target values having the lowest cost. The MPC module 312 may then test that sequence of possible target values to determine whether that sequence of possible target values satisfies the actuator constraints 348 and the output constraints 352. If so, the MPC module 312 may set the target values 266-270 to the first ones of the N values of that selected possible sequence, respectively, as discussed above.

If the actuator constraints 348 and/or the output constraints 352 are not satisfied, the MPC module 312 selects another sequence of possible target values with a next lowest cost and tests that sequence of possible target values for satisfaction of the actuator constraints 348 and the output constraints 352. The process of selecting a sequence and testing the sequence for satisfaction of the actuator constraints 348 and the output constraints 352 may be referred to as an iteration. Multiple iterations may be performed during each control loop.

The MPC module 312 performs iterations until a sequence with the lowest cost that satisfies the actuator constraints 348 and the output constraints 352 is identified. In this manner, the MPC module 312 selects the sequence of possible target values having the lowest cost while satisfying the actuator constraints 348 and the output constraints 352. If a sequence cannot be identified, the MPC module 312 may indicate that no solution is available.

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 a predetermined minimum APC; 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 following relationship:

\[
\text{Cost} = \frac{\text{Cost}_{\text{torque}}}{} + \text{Cost}_{\text{APC}} + \text{Cost}_{\text{target values}} + \text{Cost}_{\text{predicted parameters}} + \text{Cost}_{\text{output constraints}} + \text{Cost}_{\text{reference values}}
\]
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, BATRI is the base air torque request 308, and wT is a weighting value associated with the relationship between the predicted torque and the base air torque request 308. APCP is a predicted APC for the i-th one of the N control loops, MinAPC is the predetermined minimum APC, and wA is a weighting value associated with the relationship between the predicted APC and the predetermined minimum APC.

PTTOI is a possible target throttle opening for the i-th one of the N control loops, TOTref 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. PTWGWO is a possible target wastegate opening for the i-th one of the N control loops, WGORRef 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. PTIC 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.

p 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 p 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 p to zero when all of the output constraints 352 are satisfied. p 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 weighting values and the weighting values wTV, wWG, wEGR, wIP, and wEP is the cost. 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 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 the predetermined minimum APC increases and vice versa. For example only, the predetermined minimum APC may be zero or another suitable value.

Determining the cost based on the difference between the predicted APC and the predetermined minimum APC 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 one of the possible sequences having the lowest cost, the selection module 344 may select one of the possible sequences that best achieves the base air torque request 308 while minimizing APC. While the example of minimizing APC is discussed, in various implementations, an efficiency parameter may be predicted and maximized. For example, the efficiency parameter may be predicted torque divided by predicted APC or a predicted fuel consumption.

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 352 respectively. During transient operation, however, the MPC module 312 may adjust the target values 266-270 away from the reference values 352 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.

Referring now to FIG. 4, an example method of controlling the throttle valve 112, the intake cam phaser 148, the exhaust cam phaser 150, the wastegate 162 (and therefore the turbocharger), and the EGR valve 170 using MPC (model predictive control) begins at 402. At 404, the torque requesting module 224 determines the air torque request 265 based on the adjusted predicted and immediate torque requests 263 and 264. At 408, the torque conversion module 304 converts the air torque request 265 into the base air torque request 308 or into another suitable type of torque for use by the MPC module 312. At 408, the sequence determination module 316 determines possible sequences of the target values 266-270 based on the base air torque request 308.

At 410, the prediction module 323 determines the predicted parameters for each of the possible sequences of target values. The prediction module 323 determines the predicted parameters for the possible sequences based on the model 324 of the engine 102, the exogenous inputs 328, and the 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.

At 412, the cost module 332 determines the costs for the possible sequences. 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:

\[
\text{Cost} = \sum_{i=1}^{N} \left[ pT_i \cdot \left( TPI_i - \text{BATRI}_i \right)^2 + wA_i \cdot (\text{APCP}_i - 0)^2 + wT_i \cdot \left( TTV_i - \text{PTTOI}_{\text{Ref}} \right)^2 + wW_i \cdot \left( TWG_i - \text{WG}_{\text{G0}} - \text{EGRRef}_{\text{G0}} \right)^2 + wEGR_i \cdot \left( EGRRef_i - \text{EGRRef}_{\text{G0}} \right)^2 + wIP_i \cdot \left( PTIC_i - \text{ICPref}_i \right)^2 + wEP_i \cdot \left( PTECI_i - \text{ECPRef}_i \right)^2 \right].
\]
subject to the actuator constraints 348 and the output constraints 352, as discussed above.

At 414, the selection module 344 selects one of the possible sequences of the target values 266-270 based on the costs of the possible sequences. For example, the selection module 344 may select the one of the possible sequences having the lowest cost. The selection module 344 may therefore select the one of the possible sequences that best achieves the airbag actuator request 308 while minimizing the APC. Instead of or in addition to determining possible sequences of the target values 230-244 at 408 and determining the cost of each of the sequences at 412, the MPC module 312 may identify a sequence of possible target values having the lowest cost using convex optimization techniques as discussed above.

At 416, the MPC module 312 determines whether the selected one of the possible sequences satisfies the actuator constraints 348. If the selected one of the possible sequences satisfies the actuator constraints 348, the method continues at 418. Otherwise, the method continues at 420, where the MPC module 312 selects the one of the possible sequences with the next lowest cost. The method then returns to 416. In this manner, the sequence with the lowest cost that satisfies the actuator constraints 348 is used.

At 418, the first conversion module 272 converts the target wastegate opening area 266 into the target duty cycle 274 to be applied to the wastegate 162, the second conversion module 276 converts the target throttle opening area 267 into the target duty cycle 278 to be applied to the throttle valve 112. Also at 418, the third conversion module 280 converts the target EGR opening area 268 into the target duty cycle 282 to be applied to the EGR valve 170. Also at 418, the fourth conversion module 284 converts the target intake and exhaust cam phaser angles 269 and 270 into the target intake and exhaust duty cycles to be applied to the intake and exhaust cam phasers 148 and 150, respectively.

At 422, the throttle actuator module 116 controls the throttle valve 112 to achieve the target throttle opening area 267, and the phaser actuator module 158 controls the intake and exhaust cam phasers 148 and 150 to achieve the target intake and exhaust cam phaser angles 269 and 270, respectively. For example, the throttle actuator module 116 may apply a signal to the throttle valve 112 at the target duty cycle 278 to achieve the target throttle opening area 267.

Also at 422, the EGR actuator module 172 controls the EGR valve 170 to achieve the target EGR opening area 268, and the boost actuator module 164 controls the wastegate 162 to achieve the target wastegate opening area 266. For example, the EGR actuator module 172 may apply a signal to the EGR valve 170 at the target duty cycle 282 to achieve the target EGR opening area 268, and the boost actuator module 164 may apply a signal to the wastegate 162 at the target duty cycle 274 to achieve the target wastegate opening area 266. While the method is shown ending at 424, FIG. 4 may illustrate one control loop, and control loops may be executed at a predetermined rate.

Referring back to FIG. 3, a remedial action module 380 may monitor the amount of time that elapses as the MPC module 312 performs iterations and take one or more remedial actions when the elapsed time is greater than a threshold. For example, the remedial action module 380 may instruct the MPC module 312 to suspend iterations when the elapsed time of iterations started during the current control loop executed by the ECM 114 is greater than or equal to a first period. The elapsed time of iterations started during the current control loop may be referred to as the current iteration time even though the iterations may be performed during subsequent control loops. The first period may be predetermined to allow sufficient time for the other tasks to complete before the current control loop ends. For example, if the period of each control loop executed by the ECM 114 is 25 milliseconds (ms) and the other tasks require 2 ms to complete, the first period may be set to 23 ms.

The other tasks are those that are not performed by the MPC module 312 and may have a lower priority than the control loop executed by the MPC module 312. For example, the other tasks may include measuring the engine coolant temperature, measuring an exhaust gas temperature, determining a generator load, and/or determining an air conditioner load. The ECM 114 may assign a higher priority to a task with a faster loop rate relative to a task with a slower loop rate. For example, a task with a loop rate of 25 ms may be assigned a higher priority than a task with a loop rate of 50 ms. In addition, the ECM 114 may assign a higher priority to synchronous-based tasks relative to time-based tasks. The loop rate of a time-based task is known, while the loop rate of a synchronous-based task is unknown.

The remedial action module 380 may instruct the MPC module 312 to resume iterations when the other tasks are complete. If the MPC module 312 selects one of the possible sequences of the target values 266-270 before the control loop executed by the ECM 114 ends, the remedial action module 380 allows the MPC module 312 to set the target values 266-270 to the first ones of the N values of the selected sequence.

When the current iteration time is greater than or equal to a second period, the remedial action module 380 may instruct the MPC module 312 to set the target values 266-270 for the current control loop independent of the possible sequences of the target values 266-270 for the iterations started during the current control loop. The second period may be greater than the first period and/or equal to the period of the control loop executed by the ECM 114. In one example, the remedial action module 380 may instruct the MPC module 312 to set the target values 266-270 to the respective ones of the reference values 356 subject to the actuator constraints 348 and the output constraints. In a second example, the remedial action module 380 may instruct the MPC module 312 to set the target values 266-270 to the first ones of the N values of the possible sequences of the target values 266-270 selected during a previous control loop. In a third example, the remedial action module 380 may instruct the MPC module 312 to set the target values 266-270 to the second ones of the N values of the possible sequence of the target values 266-270 selected during the previous control loop.

In addition, when the current iteration time is greater than or equal to the second period, the remedial action module 380 may instruct the MPC module 312 to refrain from starting a new set of iterations during the next control loop. Then, if the MPC module 312 selects one of the possible sequences of the target values 266-270, the MPC module 312 may set the target values 266-270 for the next control loop equal to the first ones of the N values of the selected sequence. In other words, the MPC module 312 may set the target values 266-270 for the next control loop based on iterations started during the current control loop when the current iteration time extends into the period allotted for the next control loop.

In this manner, the remedial action module 380 allows the MPC module 312 to complete the iterations started during the current control loop. The MPC module 312 may then restart iterations during the control loop after the next control loop. Allowing the MPC module 312 to complete the
iterations started during the current control loop may reduce the amount of time required to complete iterations started during subsequent control loops. In addition, the loop rate of the MPC module 312 may be decreased relative to a worst-case loop rate for the longest expected iteration time. When the current iteration time is greater than a third period, the solution sought by the MPC module 312 may be infeasible or there may be another fault in the MPC module 312. Thus, the remedial action module 380 may diagnose a fault in the MPC module 312 and generate a fault signal 384. In addition, the remedial action module 380 may reset and reinitialize the MPC module 312 by, for example, clearing memory in the MPC module 312. Further, the remedial action module 380 may activate the service indicator 199 and/or set a diagnostic trouble code (DTC). The third period may be greater than the second period and may be equal to the sum of the periods of two control loops executed by the ECM 114. Thus, the current iteration time may extend into the period allotted for the control loop after the next control loop when the current iteration time is greater than the third period. When the fault signal 384 is generated, a backup module 388 may set the target values 266-270 to the reference values 356, respectively. More specifically, the backup module 388 may set the target wastegate opening area 266 to the reference wastegate opening area, the target throttle opening area 267 to the reference throttle opening area, the target EGR opening area 268 to the reference EGR opening area, the target intake cam phaser angle 269 to the reference intake cam phaser angle, and the target exhaust cam phaser angle 270 to the reference exhaust cam phaser angle. In addition, the backup module 388 may limit changes in the target values 266-270 and/or limit the torque output of the engine 102 by adjusting the target values 266-270 or by disabling certain actuators. For example, the backup module 388 may limit the torque output of the engine 102 by fully opening the wastegate 162, closing the throttle valve 112, retarding the intake and exhaust cam phasers 148 and 150, disabling fuel delivery to one or more cylinders of the engine 102, and/or disabling spark in one or more cylinders of the engine 102. The backup module 388 may set the target values 266-270 to those set by the MPC module 312 when the fault signal 384 is not generated.

In various implementations, the period required to perform a single iteration may be predetermined. In these implementations, the remedial action module 380 may monitor the number of iterations that the MPC module 312 performs and multiply the number of iterations by the predetermined iteration period to obtain the current iteration time. Alternatively, instead of comparing the current iteration time to a first period, a second period, and a third period, the remedial action module 380 may compare the number of iterations to a first value, a second value, and a third value. The first value, the second value, and the third value may be predetermined and/or may be determined by dividing the first period, the second period, and the third period by the predetermined iteration period.

Referring now to FIG. 5, a method for managing a period of a control loop executed by the MPC module 312 begins at 502. At 504, the remedial action module 380 monitors the amount of time that elapses as the MPC module 312 completes iterations started during the current control loop executed by the ECM 114. As discussed above, the elapsed time may be referred to as the current iteration time. At 506, the remedial action module 380 determines whether the current iteration time is greater than or equal to the first period. As discussed above, the first period may be predetermined to allow sufficient time for other tasks to complete before the current control loop ends. If the current iteration time is greater than or equal to the first period, the method continues at 508. Otherwise, the MPC module 312 is operating normally. Thus, the method returns to 504 and the MPC module 312 continues to perform iterations until a solution is found. If the MPC module 312 selects a sequence of possible target values while the current iteration time is less than the first period, the MPC module 312 may command the next position for each engine actuator according to the selected sequence.
the current iteration time is greater than the third period, the
method continues at 520. Otherwise, the method returns to
516 and the MPC module 312 continues to perform iterations
until a solution is obtained.

At 520, the remedial action module 380 may diagnose a
fault in the MPC module 312 and generate a fault signal 384.
Also at 520, the remedial action module 380 may reset and
reinitialize the MPC module 312 by, for example, clearing
memory in the MPC module 312. Also at 520, the remedial
action module 380 may activate the service indicator 199
and/or set a diagnostic trouble code (DTC).

Referring now to FIG. 6, example scenarios associated
with the method of FIG. 5 are illustrated. The scenarios
illustrated include a first scenario 602, a second scenario
604, a third scenario 606, and a fourth scenario 608. The
scenarios 602-608 are plotted with respect to an x-axis 610
that represents time.

In all of the scenarios 602-608, the ECM 114 executes a
first control loop from 612 to 614, the ECM 114 executes a
second control loop from 614 to 616, and the MPC module
312 starts a first set 618 of MPC iterations at 612. The time
that elapses as the MPC module 312 completes the first set
618 may be referred to as the current iteration time. In the
first scenario 602, the MPC module 312 completes the first
set 618 at 620 when the MPC module 312 finds a solution.
Thus, from 602 to 622, the ECM 114 performs other
(non-MPC) tasks 624.

The ECM 114 completes the other tasks 624 before a first
time 626. The period from 612 to the first time 626 may be
equal to the first period discussed above. Since the MPC
module 312 completes the first set 618 of MPC iterations
before the first time 626, the first scenario 602 illustrates
normal operation of the MPC module 312. In this regard,
the first scenario 602 may correspond to the case in FIG. 5
where, at 506, the current iteration time is less than the first
period.

At 614, the first control loop ends and the second control
loop begins. Since the MPC module 312 completed the first
set 618 during the first control loop, the MPC module 312
starts a second set 628 of MPC iterations at 614. In the first
and second sets 618 and 628, each square represents a single
iteration.

In the second scenario 604, the MPC module 312 does not
complete the first set 618 before the first time 626. In this
regard, the second scenario 604 may correspond to the case
in FIG. 5 where, at 506, the current iteration time is greater
than or equal to the first period. Thus, at the first time 626,
the MPC module 312 suspends the first set 618 to allow the
ECM 114 to complete the other tasks 624.

At 630, the ECM 114 completes the other tasks 624. Thus,
the MPC module 312 resumes the first set 618 of MPC
iterations. The MPC module 312 completes the first set 618
during the first control loop. Thus, at 614, the MPC module
312 starts the second set 628 of MPC iterations.

In the third scenario 606, the ECM 114 does not complete
the other tasks 624 until 614, at which point the MPC
module 312 resumes the first set 618. Thus, the MPC module
312 does not complete the first set 618 during the first
control loop. In this regard, the second scenario may corre-
spond to the case in FIG. 5 where, at 514, the current
iteration time is greater than or equal to the second period.

Since the MPC module 312 did not complete the first set
618 during the first control loop, the MPC module 312 does
not start the second set 628 at 614. In addition, the MPC
module 312 sets the target values for the first control loop
independent of the sequence of possible target values
selected upon completion of the first set 618. For example,
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 system comprising:
   a model predictive control (MPC) module that performs MPC tasks including:
   determining predicted operating parameters for a set of possible target values;
   determining a cost for the set of possible target values based on the predicted operating parameters;
   selecting the set of possible target values from multiple sets of possible target values based on the cost; and
   setting target values to the possible target values of the selected set;
   an actuator module that controls an actuator of an engine based on at least one of the target values; and
   a remedial action module that selectively takes a remedial action based on at least one of an amount of time that elapses as the MPC tasks are performed and a number of iterations of the MPC tasks that are performed.

2. The system of claim 1 wherein the remedial action module instructs the MPC module to suspend the MPC tasks when the elapsed time is greater than a first period.

3. The system of claim 2 wherein:
   the remedial action module instructs the MPC module to resume the MPC tasks when other tasks are complete; and
   the other tasks have less priority than the MPC tasks.

4. The system of claim 2 wherein:
   the remedial action module instructs the MPC module to set the target values for a present control loop independent of the possible target values for iterations started during the present control loop when the elapsed time is greater than a second period; and
   the second period is greater than the first period.

5. The system of claim 4 wherein the remedial action module instructs the MPC module to set the target values for the present control loop when the elapsed time is greater than the second period.

6. The system of claim 4 wherein:
   the MPC module sets the target values for the present control loop and a future control loop when completing the iterations started during the present control loop; and
   when the elapsed time is greater than the second period, the remedial action module instructs the MPC module to set the target values for the present control loop to the target values set for the future control loop during a previous control loop.

7. The system of claim 4 wherein the remedial action module instructs the MPC module to refrain from restarting the MPC tasks during a future control loop when the elapsed time is greater than the second period.

8. The system of claim 4 wherein:
   the remedial action module takes the remedial action when the elapsed time is greater than a third period; and
   the third period is greater than the second period.

9. The system of claim 8 wherein the remedial action includes at least one of limiting the torque output of the engine and activating a service indicator.

10. The system of claim 8 wherein the MPC module determines the cost for each of the sets of possible target values based on differences between the possible target values and reference values, the system further comprising a backup module that sets the target values for the present control loop to reference values when the elapsed time is greater than the third period.

11. A method comprising:
   performing MPC tasks including:
   determining predicted operating parameters for a set of possible target values;
   determining a cost for the set of possible target values based on the predicted operating parameters;
   selecting the set of possible target values from multiple sets of possible target values based on the cost; and
   setting target values to the possible target values of the selected set;
   controlling an actuator of an engine based on at least one of the target values; and
   selectively taking a remedial action based on at least one of an amount of time that elapses as the MPC tasks are performed and a number of iterations of the MPC tasks that are performed.

12. The method of claim 11 further comprising suspending the MPC tasks when the elapsed time is greater than a first period.

13. The method of claim 12 further comprising resuming the MPC tasks when other tasks are complete, wherein the other tasks have less priority than the MPC tasks.

14. The method of claim 12 further comprising setting the target values for a present control loop independent of the possible target values for iterations started during the present control loop when the elapsed time is greater than a second period, wherein the second period is greater than the first period.

15. The method of claim 14 further comprising setting the target values for the present control loop to the target values set during a previous control loop when the elapsed time is greater than the second period.

16. The method of claim 14 further comprising:
   setting the target values for the present control loop and a future control loop when completing the iterations started during the present control loop; and
   when the elapsed time is greater than the second period, setting the target values for the present control loop to the target values set for the future control loop during a previous control loop.

17. The method of claim 14 further comprising refraining from restarting the MPC tasks during a future control loop when the elapsed time is greater than the second period.

18. The method of claim 14 further comprising taking the remedial action when the elapsed time is greater than a third period, wherein the third period is greater than the second period.

19. The method of claim 18 wherein the remedial action includes at least one of limiting the torque output of the engine and activating a service indicator.
20. The method of claim 18 further comprising:

determining the cost for each of the sets of possible target values based on differences between the possible target values and reference values; and

setting the target values for the present control loop to reference values when the elapsed time is greater than the third period.