Previous attempts to solve these problems have included, for example, attaching a plurality of vertically-oriented or randomly-oriented lasers to the mobile robots and using the vertical or randomly-oriented lasers to detect obstacles parallel to the floor, as well as holes or drop-offs in the floor. However, there have been a number of significant disadvantages associated with such solutions, including prohibitively-high cost associated with installing, using and maintaining a multiplicity of expensive lasers, and an unacceptably high number of false positives arising, for example, from gratings in the floor, which do not necessarily need to be avoided by the mobile robot.

Summary of the Invention

Embodiments of the present invention provide methods and systems for ensuring that mobile robots are able to detect and avoid positive obstacles in a physical environment that are typically hard to detect because the obstacles do not extend vertically from the floor. Embodiments of the present invention also help to ensure that mobile robots are able to detect and avoid driving into negative obstacles, such as gaps or holes in the floor, or a flight of stairs. In general, embodiments of the present invention include a positive obstacle avoidance system for use with mobile robots, a negative obstacle avoidance system for use with mobile robots, or both a positive and negative obstacle avoidance system operating in the same mobile robot. The inventive systems and methods work for a variety of different types of mobile robots (also known as "automated guided vehicles" or "AGVs"), including without limitation autonomously-navigating mobile robots, visually-guided robots, telepresence robots, haptic input-guided robots and laser- or beacon-following robots.

In one aspect of the invention, there is provided in a mobile robot comprising a memory and a propulsion system, a method for avoiding positive obstacles in a physical environment, the method comprising: a) storing in the memory (i) a map defining a floor plan representing the physical environment and a two dimensional coordinate system delineating the floor plan, (ii) a first data structure of two-dimensional coordinates from the floor plan, the two dimensional coordinates in the first data structure representing locations in the physical environment to be avoided by the mobile robot, (iii) first laser placement information for a first laser attached to the mobile robot, said first laser being oriented to scan the physical environment in a first plane that is not parallel to the floor of the physical environment, wherein said first laser placement information includes a first laser position and a first laser tilt, and (iv) a tolerance profile comprising a ceiling offset, a floor offset, a ceiling adjustment angle and a floor adjustment

angle, b) receiving a set of laser readings from said first laser, each laser reading corresponding to a location in the physical environment where said first laser detects a physical obstacle in said first plane, and each laser reading comprising a first plane angle and a first plane distance from a given site on the mobile robot; c) for each laser reading in said set of laser readings (i) converting said each laser reading into a three-dimensional coordinate based on said first plane angle, said first plane distance, said first laser position and said first laser tilt, wherein said three-dimensional coordinate comprises an x-component, a y-component and a z-component, (ii) determining a minimum ceiling height and a maximum floor height for the three-dimensional coordinate based on the x-component, the y-component and the tolerance profile, and (iii) if the z-component is between the minimum ceiling height and the maximum floor height, adding the x-component and the y-component to the first data structure of two-dimensional coordinates to represent a new location in the physical environment to be avoided by the mobile robot; and d) causing the propulsion system to drive the mobile robot in the physical environment under control of the first data structure, wherein the propulsion system prevents the mobile robot from passing into the locations in the physical environment represented by the two-dimensional coordinates in the first data structure.

In another aspect of the invention, there is provided a mobile robot comprising a memory and a propulsion system, a method for avoiding negative obstacles in a physical environment, the method comprising: a) storing in the memory (i) a map defining a floor plan representing the physical environment and a two dimensional coordinate system delineating the floor plan, (ii) a first data structure of two-dimensional coordinates from the floor plan, the two dimensional coordinates in the first data structure representing locations in the physical environment to be avoided by the mobile robot, (iii) first laser placement information for a first laser attached to the mobile robot, said first laser being oriented to scan the physical environment in a first plane that is not parallel to the floor of the physical environment, wherein said first laser placement information includes a first laser position and a first laser tilt, and (iv) a tolerance profile comprising a maximum floor offset, a minimum floor offset, a maximum floor adjustment angle, a minimum floor adjustment angle and a maximum allowable floor gap, b) receiving a set of laser readings from said first laser, each laser reading corresponding to a location in the physical environment within said first plane, and each laser reading comprising a first plane angle and a first plane distance from a given site on the mobile robot; c) for each laser reading in said set of laser readings (i) converting said each laser reading into a three-dimensional coordinate based on said first plane angle, said first plane distance, said first laser position and said first laser tilt, wherein said three-dimensional coordinate comprises an x-component, a y-component and a z-

component, (ii) determining a maximum floor height and a minimum floor height for the three-dimensional coordinate based on the x-component, the y-component and the tolerance profile, and (iii) if the z-component is between the maximum floor height and the minimum floor height, changing an indicator in the memory to designate the x-component and the y-component of the three-dimensional coordinate as the last good floor reading, (iv) if the z-component is not between the maximum floor height and the minimum floor height, determining whether the distance G between the last good floor reading and the location in the two-dimensional coordinate system defined by the x-component and the y-component exceeds the maximum allowable floor gap, and (v) if the distance G exceeds the maximum allowable floor gap, adding the x-component, the y-component and the last good floor reading to the first data structure of two-dimensional coordinates to represent a new location in the physical environment to be avoided by the mobile robot; d) causing the propulsion system to drive the mobile robot in the physical environment under control of the first data structure, wherein the propulsion system prevents the mobile robot from passing into the locations in the physical environment represented by the two-dimensional coordinates in the first data structure.

In yet another aspect of the invention, there is provided a positive obstacle avoidance system for use with a mobile robot in a physical environment, comprising: a) a first laser attached to the mobile robot, said first laser being oriented to scan the physical environment in a first plane that is not parallel to the floor of the physical environment; b) a memory for storing (i) a map defining a floor plan representing the physical environment and a two dimensional coordinate system delineating the floor plan, (ii) a first data structure of two-dimensional coordinates from the floor plan, each two dimensional coordinate in the first data structure representing a location in the physical environment to be avoided by the mobile robot, (iii) first laser placement information for said first laser, said first laser placement information including a first laser position and a first laser tilt, and (iv) a tolerance profile comprising a ceiling offset, a floor offset, a ceiling adjustment angle and a floor adjustment angle, c) a laser controller for receiving a set of laser readings from said first laser, each laser reading corresponding to a location in the physical environment where said first laser detects a physical obstacle in said first plane, and each laser reading comprising a first plane angle and a first plane distance from a given site on the mobile robot; d) positive obstacle avoidance engine that, for each laser reading in said set of laser readings (i) converts said each laser reading into a three-dimensional coordinate based on said first plane angle, said first plane distance, said first laser position and said first laser tilt, wherein said three-dimensional coordinate comprises an x-component, a y-

component and a z-component, (ii) determines a minimum ceiling height and a maximum floor height for the three-dimensional coordinate based on the x-component, the y-component and the tolerance profile, and (iii) if the z-component is between the minimum ceiling height and the maximum floor height, adds the x-component and the y-component to the first data structure of two-dimensional coordinates to represent a new location in the physical environment to be avoided by the mobile robot; and e) a propulsion system that drives the mobile robot in the physical environment under control of the first data structure, the propulsion system being configured to prevent the mobile robot from passing into the locations in the physical environment represented by the two-dimensional coordinates in the first data structure.

In still another aspect of the invention, there is provided a negative obstacle avoidance system for use with a mobile robot in a physical environment, comprising: a) a first laser attached to the mobile robot, said first laser being oriented to scan the physical environment in a first plane that is not parallel to the floor of the physical environment; b) a memory for storing (i) a map defining a floor plan representing the physical environment and a two dimensional coordinate system delineating the floor plan, (ii) a first data structure of two-dimensional coordinates from the floor plan, the two dimensional coordinates in the first data structure representing locations in the physical environment to be avoided by the mobile robot, (iii) first laser placement information for said first laser, the first laser placement information including a first laser position and a first laser tilt, and (iv) a tolerance profile comprising a maximum floor offset, a minimum floor offset, a maximum floor adjustment angle, a minimum floor adjustment angle and a maximum allowable floor gap, c) a laser controller for receiving a set of laser readings from said first laser, each laser reading corresponding to a location in the physical environment within said first plane, and each laser reading comprising a first plane angle and a first plane distance from a given site on the mobile robot; and d) a negative obstacle avoidance engine that, for each laser reading in said set of laser readings (i) converts said each laser reading into a three-dimensional coordinate based on said first plane angle, said first plane distance, said first laser position and said first laser tilt, wherein said three-dimensional coordinate comprises an x-component, a y-component and a z-component, (ii) determines a maximum floor height and a minimum floor height for the three-dimensional coordinate based on the x-component, the y-component and the tolerance profile, and (iii) if the z-component is between the maximum floor height and the minimum floor height, changes an indicator in the memory to designate the x-component and the y-component of the three-dimensional coordinate as the last good floor reading coordinate, (iv) if the z-component is not between the maximum

floor height and the minimum floor height, determines whether the distance G between the last good floor reading coordinate and the location in the two-dimensional coordinate system defined by the x-component and the y-component exceeds the maximum allowable floor gap, and (v) if the distance G exceeds the maximum allowable floor gap, adds the x-component, the y-component and the last good floor reading coordinate to the first data structure of two-dimensional coordinates to represent another location in the physical environment to be avoided by the mobile robot; and e) a propulsion system that drives the mobile robot in the physical environment under control of the first data structure, the propulsion system being configured to prevent the mobile robot from passing into the locations in the physical environment represented by the two-dimensional coordinates in the first data structure.

~~In one aspect of the invention, there~~ There is also provided a positive obstacle avoidance system for use with a mobile robot in a physical environment, comprising a first laser attached to the mobile robot, a memory, a laser controller, a positive obstacle avoidance engine and a propulsion system. The first laser attached to the mobile robot is oriented to scan the physical environment in a first plane that is not parallel to the floor of the physical environment. The memory stores initial operating parameters and preferences for the positive obstacle avoidance engine, including: (1) a map defining a floor plan representing the physical environment and a two dimensional coordinate system delineating the floor plan, (2) a first data structure of two-dimensional coordinates from the floor plan, each two dimensional coordinate in the first data structure representing a location in the physical environment to be avoided by the mobile robot, (3) first laser placement information for the first laser, including the first laser's position on the mobile robot and the first laser's orientation (or tilt angle), and (4) a tolerance profile for the

case, the laser controller receives a second set of laser readings from the second laser, each laser reading corresponding to a location in the physical environment where the second laser detects a physical obstacle in the second plane. The positive obstacle avoidance engine performs the same calculations for each laser reading received from the second set of laser readings in order to determine whether the detected obstacle represents the expected floor or ceiling, based on distance and angle from the robot, or otherwise represents some obstacle located between the floor and the ceiling in the physical environment that needs to be avoided. Thus, the positive obstacle avoidance engine converts each laser reading into a second three-dimensional coordinate based on the second plane angle (*theta*), the second plane distance (*r*), the second laser position and the second laser tilt. The positive obstacle avoidance engine then determines an minimum allowable ceiling height and a maximum allowable floor height for the second three-dimensional coordinate based on the x-component of the second three-dimensional coordinate, the y-component of the second three-dimensional coordinate and the tolerance profile. Then the engine determines whether the second z-component lies between the allowable floor height and the allowable ceiling height based on the z-component's distance from the robot. If so, the positive obstacle avoidance engine adds the x-component and the y-component of the second three-dimensional coordinate to the second data structure of two-dimensional coordinates to represent another location in the physical environment to be avoided by the mobile robot. In this manner, the positive obstacle avoidance engine builds and populates a second collection or list of two-dimensional coordinates from the floor plan that the mobile robot should avoid while driving about the physical environment. The propulsion system drives the mobile robot about the physical environment under control or influence of the first data structure and the second data structure, while preventing the mobile robot from passing into the locations in the physical environment represented by the two-dimensional coordinates in both the first data structure and the second data structure. It will be understood by those skilled in the art that embodiments of the present invention may in fact store all of the two-dimensional coordinates for both the first laser and the second laser in a single data structure, or a multiplicity of different data structures, instead of two discreet data structures, without departing from the scope of the claimed invention. Any number of data structures may be used, so long as the propulsion system accesses the stored two-dimensional coordinate data to determine which parts of the floor plan should not be driven into by the mobile robot.

~~In another aspect, e~~Embodiments of the present invention also provide a negative obstacle avoidance system for use with a mobile robot in a physical environment. The negative obstacle avoidance system operates to prevent the mobile robot from driving into a hole or ditch, driving

The engine then determines if the z-component falls between the maximum allowable floor height and the minimum allowable floor height. If it does, the negative obstacle avoidance system changes an indicator, such as a flag in the memory to designate the x-component and the y-component of the three-dimensional coordinate as the coordinate corresponding to the last good floor reading. If the z-component does not fall between the maximum allowable floor height and the minimum allowable floor height, then the negative obstacle avoidance engine determines whether the distance G between the last good floor reading coordinate and the location in the two-dimensional coordinate system defined by the x-component and the y-component exceeds the maximum allowable floor gap stored in the memory. If the distance G exceeds the maximum allowable floor gap, the negative obstacle avoidance engine adds the x-component, the y-component and the last good floor reading coordinates to the first data structure of two-dimensional coordinates to represent another location in the physical environment to be avoided by the mobile robot. The propulsion system then drives the mobile robot in the physical environment under control of the first data structure, so as to prevent the mobile robot from passing into the locations in the physical environment represented by the two-dimensional coordinates in the first data structure. Thus, the mobile robot, operating under the control of the propulsion system, which itself operates under the influence of the first data structure of two-dimensional coordinates identifying all of the two-dimensional coordinates in the floor plan to be avoided, avoids driving into the gap, ditch or hole, or off of a cliff.

~~In yet another aspect t~~There is provided a method for avoiding positive obstacles in a mobile robot comprising a memory and a propulsion system. The first step in the method comprises storing the map, the first data structure of two-dimensional coordinates, the first laser placement information and the tolerance profile in the memory. In the next step, a set of laser readings from the first laser are received, each laser reading corresponding to a location in the physical environment where said first laser detects a physical obstacle in the first plane, and each laser reading having a first plane angle (*theta*) and a first plane distance (radius = *r*) from a given spot on the mobile robot. Next, each laser reading in the set of laser readings is automatically processed by the mobile robot by: (1) converting each laser reading into a three-dimensional coordinate based on the first plane angle (*theta*), said first plane distance (*r*), the first laser position and the first laser tilt. The three-dimensional coordinate includes an x-component, a y-component and a z-component. Then, a minimum ceiling height and a maximum floor height for the three-dimensional coordinates are determined based on the x-component, the y-component and the tolerance profile. If the z-component falls between the minimum ceiling height and the maximum floor height, then the laser reading is considered to have detected an obstacle that

(such as a table surface or overhang) that should be avoided, and the x-component and the y-component of the three-dimensional coordinate (which point to the spot on the floor below the table or overhang) are added to the first data structure of two-dimensional coordinates to represent a new location in the physical environment to be avoided by the mobile robot. In the final step, the propulsion system drives the mobile robot in the physical environment under the influence or control of the first data structure. As previously stated, this means the propulsion system periodically checks the data in the first data structure of two-dimensional coordinates and prevents the mobile robot from passing into the locations in the physical environment represented by the two-dimensional coordinates in the first data structure. By avoiding the spots on the floor below the table or overhang, the mobile robot also avoids driving into the table or overhang. In some embodiments, the mobile robot does its own path planning and navigation. In these embodiments, the method further includes the steps of: (1) receiving on the mobile robot a command to move from a current position to a specified location in the physical environment, (2) calculating on the mobile robot, in accordance with the floor plan, a path between the mobile robot's current position and the specified location that avoids the locations in the physical environment represented by the coordinates in the first data structure of two-dimensional coordinates, and (3) activating the propulsion system to automatically drive the mobile robot along the path.

~~In still another aspect, the present invention provides~~ Also disclosed is a method for avoiding negative obstacles in a physical environment using a mobile robot comprising a memory and a propulsion system. In this aspect, the method begins by storing in the memory a map defining the floor plan representing the physical environment and a two dimensional coordinate system delineating the floor plan, a first data structure of two-dimensional coordinates from the floor plan, the two dimensional coordinates in the first data structure representing locations in the physical environment to be avoided by the mobile robot, first laser placement information for a first laser attached to the mobile robot, the first laser being oriented to scan the physical environment in a first plane that is not parallel to the floor of the physical environment. The first laser placement information includes a first laser position and a first laser tilt, and a tolerance profile comprising a maximum floor offset, a minimum floor offset, a maximum floor adjustment angle, a minimum floor adjustment angle and a maximum allowable floor gap. The next step comprises receiving a set of laser readings from the first laser, each laser reading corresponding to a location in the physical environment within the first plane, and each laser reading comprising a first plane angle and a first plane distance from a given site on the mobile robot. Then, each laser reading in the set of laser readings is converted into a three-dimensional coordinate based on the first plane