

SYSTEM AND METHOD FOR INSPECTING VEHICLE TYRES

Cross Reference to Related Application(s)

- 5 The present disclosure claims the benefit of Singapore Patent Application No. 10202102107P filed on 02 March 2021, which is incorporated in its entirety by reference herein.

Technical Field

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The present disclosure generally relates to inspection of vehicle tyres. More particularly, the present disclosure describes various embodiments of an inspection system, inspection method, and inspection robot for inspecting the tyres of a vehicle such as a bus.

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Background

Vehicles 100 like buses and trucks have tyres 110 that enable the vehicles 100 to drive on roads, as shown in Figure 1A. Tyres 110 have one of the shortest useable
20 lifespans as they are subjected to constant wear due to continuous operation. Moreover, if the vehicles 100 are used in tropical climates, high temperatures in these climates tend to worsen wear of the tyres 110. As shown in Figure 1B, tyres 110 have treads 120 with grooves that create tyre-to-road energy and grip transfer to minimize slippage on roads. Under wear, these treads 120 constantly erode and causes
25 irregular baldness (or bald areas 130) of the tyres 110 depending on the force interactions between the tyres 110 and the road. As a standard requirement, a minimum tyre tread depth is necessary for safe operation of vehicles 100 under their own load and speed expectations. Excessive wearing of tyres 110 can result in potential suspensions of vehicles 100 or even catastrophic failures. Regular inspection
30 and maintenance of the tyres 110 are thus necessary to avoid excessive wearing of tyres 110.

A bus operator who has a fleet of buses is required to keep the bus tyres 110 in good working condition for integrity of the buses and safety of people riding in the buses. These buses can operate up to 18 hours a day and thus require regular maintenance. The tyre tread depth or depth of the grooves is normally checked by qualitative visual inspection, which is often unreliable as tyres 110 may still pass the inspection if the inspector decides that the treads 120 are still in working condition when the tread depth has in fact worn down excessively to less than the allowable minimum limit (e.g. 4 mm). Tyres 110 with worn treads 120 can be retreaded to repair tyres 110 and extend their lifespans, but unreliable visual inspections can cause the tyres 110 to miss a retreading schedule. These tyres 110 are sent back to the roads and the treads 120 are worn down even more. However, retreading is not possible for excessively worn treads 120 that are less than the allowable minimum limit, and the tyres 110 must then be replaced which increases operational cost for the bus operator.

The tyre tread depth can be measured quantitatively using a tread depth gauge 140 as shown in Figure 1C. However, the tread depth gauge 140 can only be used to measure an approximate tread depth at specific points on the surface of the tyres 110, and measurements can vary between different users depending on their experience. This manual way of using the tread depth gauge 140 is time consuming, inaccurate, has low repeatability, and can only measure a single point of the tyre surface each time. It is not practical to use the tread depth gauge 140 to measure the tread depth across most of the surface of the tyres 110. Moreover, for buses with outer and inner tyres 110, it is difficult for the inner tyres 110 to be inspected visually or by manual measurement using the tread depth gauge 140.

Current methods of inspecting tyres 110 cannot reliably measure the depth of the tyre treads 120 across most of the surface of the tyres 110. Excessively worn tyres 110 do not satisfy commercial requirements for fleet operators and continuing to use such tyres 110 in their vehicles 100 would compromise vehicle safety and may be illegal. On the other hand, some fleet operators may take a more risk averse approach and replace tyres 110 even when the treads 120 are still in working condition and the tread depth still meet allowable minimum limit. Premature replacement of tyres 110 can be

regarded as wasteful and increases the operational cost for the fleet operators, especially for large fleet operators with many vehicles 100.

Therefore, in order to address or alleviate at least one of the aforementioned problems
5 and/or disadvantages, there is a need to provide an improved alternative for inspection of vehicle tyres.

Summary

10 According to a first aspect of the present disclosure, there is an inspection robot for inspecting tyres of a vehicle. The inspection robot comprises:

- a chassis body comprising a driving mechanism for driving the inspection robot;

- 15 a robotic arm assembly coupled to the chassis body for actuating around a set of tyres of the vehicle, the robotic arm assembly comprising:

- a first arm actuatable around an arc surface of the set of tyres, the arc surface comprising a tyre tread; and

- 20 a second arm coupled to the first robotic arm and actuatable around a sidewall of the set of tyres; and

- first stereo sensors moveable by the first arm around the arc surface for capturing stereo images of the tyre tread,

- wherein a 3D image profile of the tyre tread is constructable from the stereo images of the tyre tread for inspection of the tyre tread.

25 According to a second aspect of the present disclosure, there is an inspection method for inspecting tyres of a vehicle. The inspection method comprises:

- driving an inspection robot towards the vehicle, the inspection robot comprising a robotic arm assembly for actuating around a set of tyres of the vehicle;

- 30 actuating a first arm of the robotic arm assembly around an arc surface of the set of tyres, the arc surface comprising a tyre tread;

- actuating a second arm of the robotic arm assembly around a sidewall of the set of tyres, the second arm coupled to the first arm;

moving, by the first arm, first stereo sensors around the arc surface; and capturing, using the first stereo sensors, stereo images of the tyre tread, wherein a 3D image profile of the tyre tread is constructable from the stereo images of the tyre tread for inspection of the tyre tread.

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According to a third aspect of the present disclosure, there is a computer system for inspecting tyres of a vehicle. The computer system comprises:

a transceiver module configured for receiving, from an inspection robot configured for inspecting the vehicle, stereo images of a tyre tread around an arc surface of a set of tyres of the vehicle;

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an image processing module configured for constructing a 3D image profile of the tyre tread from the stereo images of the tyre tread; and

a data processing module configured for inspecting the set of tyres by comparing the 3D image profile of the tyre tread against a database.

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According to a fourth aspect of the present disclosure, there is a computerized method for inspecting tyres of a vehicle. The computerized method comprises:

receiving, from an inspection robot configured for inspecting the vehicle, stereo images of a tyre tread around an arc surface of a set of tyres of the vehicle;

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constructing a 3D image profile of the tyre tread from the stereo images of the tyre tread; and

inspecting the set of tyres by comparing the 3D image profile of the tyre tread against a database.

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According to a fifth aspect of the present disclosure, there is an inspection system for inspecting tyres of a vehicle. The inspection system comprises:

an inspection robot comprising:

a chassis body comprising a driving mechanism for driving the inspection robot;

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a robotic arm assembly coupled to the chassis body for actuating around a set of tyres of the vehicle, the robotic arm assembly comprising:

a first arm actuatable around an arc surface of the set of
tyres, the arc surface comprising a tyre tread; and
a second arm coupled to the first robotic arm and
actuatable around a sidewall of the set of tyres; and
5 first stereo sensors moveable by the first arm around the arc
surface for capturing stereo images of the tyre tread; and
a computer system communicative with the inspection robot, the
computer system comprising:
a transceiver module configured for receiving the stereo images of the
10 tyre tread from the inspection robot;
an image processing module configured for constructing a 3D image
profile of the tyre tread from the stereo images of the tyre tread; and
a data processing module configured for inspecting the set of tyres by
comparing the 3D image profile of the tyre tread against a database.

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An inspection system, method, and robot for inspecting tyres of a vehicle according to
the present disclosure are thus disclosed herein. Various features, aspects, and
advantages of the present disclosure will become more apparent from the following
detailed description of the embodiments of the present disclosure, by way of non-
20 limiting examples only, along with the accompanying drawings.

Brief Description of the Drawings

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Figure 1A is an illustration of a vehicle with tyres.

Figure 1B is an illustration of tyres at different stages of wear.

Figure 1C is an illustration of using a tread depth gauge on a tyre.

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Figure 2 is an illustration of an inspection system for inspecting tyres of a vehicle,
according to embodiments of the present disclosure.

Figure 3A is an illustration of an inspection robot of the inspection system.

Figure 3B is another illustration of the inspection robot.

Figure 4A is an illustration of the inspection robot inspecting a set of tyres.

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Figure 4B is another illustration of the inspection robot inspecting the set of tyres.

Figure 5 is a flowchart illustration of an inspection method for inspecting tyres of a vehicle

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Figure 6 is a flowchart illustration of a computerized method for inspecting tyres of a vehicle.

Figure 7A is an illustration of an unrolling function to construct a 3D image profile of the tyre tread.

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Figure 7B is an illustration of a 3D quadrangle used in the unrolling function.

Figure 8A is an illustration of the 3D image profile of the tyre tread.

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Figure 8B is an illustration of the 3D image profile of the tyre tread in the form of depth map.

Figure 8C is an illustration of a depth map and an RGB image of the tyre tread of a new set of tyres.

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Figure 8D is an illustration of a depth map and an RGB image of the tyre tread of a worn set of tyres.

Figure 9 is an illustration of the inspection robot and a surface pressure sensor inspecting a set of tyres.

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Detailed Description

For purposes of brevity and clarity, descriptions of embodiments of the present disclosure are directed to an inspection system, method, and robot for inspecting tyres of a vehicle, in accordance with the drawings. While aspects of the present disclosure will be described in conjunction with the embodiments provided herein, it will be understood that they are not intended to limit the present disclosure to these embodiments. On the contrary, the present disclosure is intended to cover alternatives, modifications and equivalents to the embodiments described herein, which are included within the scope of the present disclosure as defined by the appended claims.

Furthermore, in the following detailed description, specific details are set forth in order to provide a thorough understanding of the present disclosure. However, it will be recognized by an individual having ordinary skill in the art, i.e. a skilled person, that the present disclosure may be practiced without specific details, and/or with multiple details arising from combinations of aspects of particular embodiments. In a number of instances, well-known systems, methods, procedures, and components have not been described in detail so as to not unnecessarily obscure aspects of the embodiments of the present disclosure.

In embodiments of the present disclosure, depiction of a given element or consideration or use of a particular element number in a particular figure or a reference thereto in corresponding descriptive material can encompass the same, an equivalent, or an analogous element or element number identified in another figure or descriptive material associated therewith.

References to “an embodiment / example”, “another embodiment / example”, “some embodiments / examples”, “some other embodiments / examples”, and so on, indicate that the embodiment(s) / example(s) so described may include a particular feature, structure, characteristic, property, element, or limitation, but that not every embodiment / example necessarily includes that particular feature, structure, characteristic, property, element or limitation. Furthermore, repeated use of the phrase “in an embodiment / example” or “in another embodiment / example” does not necessarily refer to the same embodiment / example.

The terms “comprising”, “including”, “having”, and the like do not exclude the presence of other features / elements / steps than those listed in an embodiment. Recitation of certain features / elements / steps in mutually different embodiments does not indicate that a combination of these features / elements / steps cannot be used in an
5 embodiment.

As used herein, the terms “a” and “an” are defined as one or more than one. The use of “/” in a figure or associated text is understood to mean “and/or” unless otherwise indicated. The term “set” is defined as a non-empty finite organization of elements that
10 mathematically exhibits a cardinality of at least one (e.g. a set as defined herein can correspond to a unit, singlet, or single-element set, or a multiple-element set), in accordance with known mathematical definitions. The recitation of a particular numerical value or value range herein is understood to include or be a recitation of an approximate numerical value or value range. The terms “first”, “second”, etc. are used
15 merely as labels or identifiers and are not intended to impose numerical requirements on their associated terms.

In representative or exemplary embodiments of the present disclosure, with reference to Figure 2, there is an inspection system 200 for inspecting the tyres 110 of a vehicle
20 100 such as a car or a bus. The inspection system 200 includes an inspection robot 300 and a computer system 400 communicative with the inspection robot 300 to cooperatively inspect one or more sets of the tyres 110. Notably, the vehicle 100 has multiple sets of tyres 110 located at both sides of the wheel axles of the vehicle 100. For example, a car has four sets of tyres 110 at the front and rear wheel axles,
25 specifically at the front left, front right, rear left, and rear left. For larger vehicles 100 like a bus, the bus may have three (or more) wheel axles, each side of each wheel axle having a respective set of tyres 110. Further, each set of tyres 110 of the bus may include a plurality of tyres 110, such as an outer tyre 110a and an inner tyre 110b.

30 As shown in Figures 3A and 3B, the inspection robot 300 includes a chassis body 310 having a driving mechanism 320 for driving the inspection robot 300. For example, the driving mechanism 320 includes a set of wheels 322 and a propulsion device. Preferably, the driving mechanism 320 is configured to drive the inspection robot 300

omnidirectionally. The inspection robot 300 further includes a robotic arm assembly 330 coupled to the chassis body 310 for actuating around a set of tyres 110 of the vehicle 100.

5 Further as shown in Figures 4A and 4B, the robotic arm assembly 330 includes a first arm 332 actuatable around an arc surface 112 of the set of tyres 110, the arc surface 112 having a tyre tread 120. The robotic arm assembly 330 further includes a second arm 334 coupled to the first arm 332 and actuatable around a sidewall 114 of the set of tyres 110. More specifically, the second arm 334 is moveably coupled to the chassis
10 body 310 such that the first arm 332 and second arm 334 are actuatable around the set of tyres 110. For example, the robotic arm assembly 330 is aligned to the wheel axle of the set of tyres 110 and the first arm 332 and second arm 334 are rotatable about the wheel axle.

15 The inspection robot 300 further includes first stereo sensors 342 moveable by the first arm 332 around the arc surface 112 for capturing stereo images of the tyre tread 120. A 3D image profile of the tyre tread 120 can be constructed from the stereo images of the tyre tread 120 for inspection of the tyre tread 120.

20 In some embodiments, the inspection robot 300 further includes second stereo sensors 344 moveable by the second arm 334 around the sidewall 114 for capturing stereo images of the sidewall 114. The second stereo sensors 344 may be referred to as the lateral stereo sensors as the second arm 334 is positioned on the lateral side of the sidewall 114 during actuation. A 3D image profile of the sidewall 114 is
25 constructable from the stereo images of the sidewall 114 for inspection of the sidewall 114.

In some embodiments, the inspection robot 300 further includes third stereo sensors 346 moveable by the first arm 332 around the arc surface 112 of the set of tyres 110
30 for capturing stereo images of the tyre tread 120. For example as shown in Figure 4A, the set of tyres 110 includes an outer tyre 110a and an inner tyre 110b. Further as shown in Figure 3B, the first stereo sensors 342 are moveable by the first arm 332 around the arc surface 112 of the outer tyre 110a for capturing stereo images of the

tyre tread 120 of the outer tyre 110a, and the third stereo sensors 346 are moveable by the first arm 332 around the arc surface 112 of the inner tyre 110b for capturing stereo images of the tyre tread 120 of the inner tyre 110b. The 3D image profile of the tyre tread 120 of the set of tyres 110 including the outer tyre 110a and inner tyre 110b is hence constructable from the respective stereo images of the tyres 110 captured by the first stereo sensors 342 and third stereo sensors 346.

Each set of the stereo sensors 342,344,346 includes two (or more) stereo sensors and operates on the principle of stereovision which is a machine vision technique for 3D measurements with depth information, similar to 3D perception in human binocular vision. The two stereo sensors are aligned to each other and separated by a fixed distance. After calibrating the two stereo sensors based on their 3D spatial relationship, such as the separation distance and any tilt, each stereo sensor can capture a respective stereo image of the same object. Matching pixels from the stereo images can be triangulated and the stereo images can be combined to calculate depth information of the object, thereby obtaining a 3D measurement of the object.

The inspection system 200 is installed in an inspection facility such as a vehicle depot (e.g. bus depot) which has parking bays for the vehicles 100. The inspection system 200 includes a base station 250 for docking and charging the inspection robot 300. The inspection robot 300 is normally docked at the base station 250 in standby or sleep mode. When a vehicle 100 enters the vehicle depot, the computer system 400 via a sensor installed in the inspection facility or at the base station 250 detects that the vehicle 100 has parked at a parking bay. The computer system 400 then sends a control signal to the base station 250 to wake and deploy the inspection robot 300 to the vehicle 100.

As the location of the parking bay relative to the base station 250 is known, the inspection robot 300 may drive autonomously along a preprogrammed path 252 towards the vehicle 100 to inspect the tyres 110. The driving mechanism 320 may include a set of obstacle detection devices, such as Lidar sensors, to facilitate autonomous driving of the inspection robot 300. When the inspection robot 300 is approaching the vehicle 100, the inspection robot 300 aligns itself to a set of tyres 110 to inspect the

set of tyres 110. For example, the robotic arm assembly 330 is aligned to the wheel axle of the tyres 110. The inspection robot 300 may detect the position of the set of tyres 110, such as front left or rear right, before inspecting it. After inspecting the set of tyres 110, the inspection robot 300 drives around the vehicle 100 to inspect the other sets of tyres 110 sequentially. After inspecting all the sets of tyres 110, the inspection robot 300 returns to the base station 250 for recharging.

For each set of tyres 110, the inspection robot 300 may measure parameters such as distance between the tyres 110 and the inspection robot 300, orientation of the inspection robot 300 relative to the tyres 110, height of the tyres 110 relative to the ground, and ambient lighting, to optimize the inspection. For example, the inspection robot 300 may include an illumination device for detecting the ambient lighting around the tyres 110, and if the ambient lighting is too dark, the illumination device can emit light towards the tyres 110. The illumination device can provide adjustable lighting as the inspection robot 300 is positioned at the undercarriage of the vehicle 100 during inspection where there is usually poor lighting.

With reference to Figure 5, the inspection robot 300 is configured to perform an inspection method 500 for inspecting the tyres 110 of the vehicle 100. The inspection method 500 includes a step 510 of driving the inspection robot 300 towards the vehicle 100. The inspection method 500 further includes a step 520 of actuating the first arm 332 around the arc surface 112 of the set of tyres 110, and a step 530 of actuating the second arm 334 around the sidewall 114 of the set of tyres 110. The inspection method 500 further includes a step 540 of moving, by the first arm 332, the first stereo sensors 342 around the arc surface 112. The inspection method 500 further includes a step 550 of capturing, using the first stereo sensors 342, stereo images of the tyre tread 120.

In some embodiments, the inspection method 500 further includes a step of moving, by the second arm 334, the second stereo sensors 344 around the sidewall 114, and a step of capturing, using the second stereo sensors 344, stereo images of the sidewall 114.

In some embodiments, the set of tyres 110 includes an outer tyre 110a and an inner tyre 110b. The step 540 moves, by the first arm 332, the first stereo sensors 342 around the arc surface 112 of the outer tyre 110a. The step 540 captures, using the first stereo sensors 342, stereo images of the tyre tread 120 of the outer tyre 110a.

5 The inspection method 500 further includes a step of moving, by the first arm 332, the third stereo sensors 346 around the arc surface 112 of the inner tyre 110b, and a step of capturing, using the third stereo sensors 346, stereo images of the tyre tread 120 of the inner tyre 110b.

10 The stereo images of the tyre tread 120 and side wall 114 of the set of tyres 110, which may have a single-tyre or multi-tyre configuration, are captured using the first stereo sensors 342, second stereo sensors 344, and third stereo sensors 346 as they move around the set of tyres 110 by actuation of the first arm 332 and second arm 334. This allows the stereo sensors 342,344,346 to scan and capture stereo images across most

15 of the tyre surfaces including the arc surface 112 and sidewall 114. For example, the arms 332,334,346 may be actuated across an angle of up to 300° or more. The arc surface 112 scanned by the first stereo sensors 342 and third stereo sensors 346 may thus subtend an angle of up to 300° or more, capturing most of the surface curvature of the tyres 110. Compared to existing manual methods like the tread depth gauge

20 140, a significantly larger area of the tyres 110 can be inspected, especially the tread depth at most of the arc surface 112, and the tyre 110 can be more reliably and holistically evaluated.

The inspection robot 300 may be configured to detect whether the set of tyres 110 has

25 a single-tyre or multi-tyre configuration. Upon detecting that the set of tyres 110 has a multi-tyre configuration include an outer tyre 110a and an inner tyre 110b, the third stereo sensors 346 may be deployed such that the first stereo sensors 342 scan the outer tyre 110a and the third stereo sensors 346 scan the inner tyre 110b. The 3D image profile of the tyre tread 120 of the inner tyre 110b can be constructed from the

30 stereo images captured by the third stereo sensors 346. The 3D image profile can be used to inspect the inner tyre 110b which is normally beyond the line of sight of human-based inspections, since it is difficult to reach into the inner tyre 110b and there is poor lighting around the inner tyre 110b. The first and third stereo sensors 342,346 can thus

collectively capture stereo images of tyres 110 with a multi-tyre configuration for more reliable inspection than human-based inspections.

5 The robotic arm assembly 330 may be configured to be retractable into the chassis body 310. For example, the first arm 332 is foldable onto the second arm 334 and the second arm 334 is foldable onto the chassis body 310. This compacts the inspection robot 300 as it drives between the base station 250 and the vehicle 100, only deploying the robotic arm assembly 330 when the inspection robot 300 is positioned at the vehicle 100 to inspect the tyres 110. As shown in Figure 3B, the first arm 332 may include a proximal section for holding the first stereo sensors 342, and a distal section for holding the third stereo sensors 346. Further as shown in Figure 3A, the distal section may be normally folded onto the proximal section and may be unfolded outward if the third stereo sensors 346 are needed to scan tyres 110 with a multi-tyre configuration.

15 As mentioned above, the inspection system 200 includes an inspection robot 300 and a computer system 400 communicative with the inspection robot 300 to cooperatively inspect the tyres 110. The communication between the computer system 400 and the inspection robot 300 may be by wireless communication protocols such as Wi-Fi or Bluetooth, or alternatively by wired communication such as data cables.

As shown in Figure 2, the computer system 400 includes a transceiver module 410 for receiving the stereo images of the tyre tread 120 from the inspection robot 300. The computer system 400 further includes an image processing module 420 for constructing the 3D image profile of the tyre tread 120 from the stereo images of the tyre tread 120. The computer system 400 further includes a data processing module 430 for inspecting the set of tyres 110 based on the 3D image profile of the tyre tread 120 and a database 440 that stores standard reference data for comparison of the 3D image profile. The standard reference data may be derived from tyre manufacturer guidelines and/or results from past inspections of tyres 110.

With reference to Figure 6, the computer system 400 is configured to perform a computer-implemented or computerized method 600 for inspecting the tyres 110 of

the vehicle 100. The computerized method 600 includes a step 610 of receiving, using the transceiver module 410, the stereo images of the tyre tread 120 from the inspection robot 300. The computerized method 600 further includes a step 620 of constructing, using the image processing module 420, the 3D image profile of the tyre tread 120 from the stereo images of the tyre tread 120. The computerized method 600 further includes a step 630 of inspecting, using the data processing module 430, the set of tyres 110 by comparing the 3D image profile of the tyre tread 120 against the database 440.

As described above, the stereo images of the tyre tread 120 are captured using the first stereo sensors 342 as they move around the set of tyres 110 by actuation of the first arm 332, such as rotation over an angle of 300° . The first arm 332 pauses at a few instances during this actuation to allow the first stereo sensors 342 to capture the stereo images of the tyre tread 120 at a single area of the arc surface 112. Multiple sets of stereo images of the tyre tread 120 at multiple areas of the arc surface 112 are captured as the first arm 332 completes the actuation. Preferably, these multiple sets of stereo images have overlapping portions so that they can be combined or stitched together to capture most of the arc surface 112.

In many embodiments, constructing the 3D image profile of the tyre tread 120 using the image processing module 420 includes steps of calculating a set of disparity maps from the stereo images of the tyre tread 120 and constructing a set of 3D point clouds from the disparity maps. Each disparity map is calculated from the respective stereo images of a corresponding area of the arc surface 112, and each 3D point cloud is constructed from the respective disparity map. As mentioned above, matching pixels from the stereo images can be triangulated to calculate 3D coordinates of the tyre tread 120. The disparity map is calculated based on the distance between each pixel in one stereo image and a matching pixel in the other stereo image. The depth (z) of each pixel can be calculated based on the disparities of the corresponding pixels. Given that the 3D coordinates (x,y,z) are known from the disparity map, the 3D point cloud can be constructed.

Constructing the 3D image profile of the tyre tread 120 further includes steps of merging the 3D point clouds to form a merged 3D point cloud 700, as shown in Figure 7A, and constructing the 3D image profile of the tyre tread 120 from the merged 3D point cloud 700. Merging of the 3D point clouds is performed using a point cloud registration method. For example, the point cloud registration method includes a rigid transformation algorithm that assume the 3D point clouds differ by rotation and translation only but preserve the distance between every pair of points. The 3D image profile of the tyre tread 120 constructed from the 3D point cloud 700 extends across most of the arc surface 112, allowing most of the tyre surface to be inspected.

In some embodiments, constructing the 3D image profile of the tyre tread 120 includes a step of denoising the 3D point cloud 700 and/or each of the constituent 3D point clouds, i.e. each 3D point cloud in the set of 3D point clouds. For example, denoising of the merged 3D point cloud 700 is performed using a cross-in tray function as defined below.

$$f(X) = -0.0001 \left(\left| \sin(x_1) \sin(x_2) \exp \left(\left| 100 - \frac{\sqrt{x_1^2 + x_2^2}}{\pi} \right| \right) \right| + 1 \right)^{0.1}$$

The cross-in tray function has four global minima points (X^*) as defined below.

$$f(X^*) = -2.0626, \text{ where } X^* = (\pm 1.3491, \pm 1.3491)$$

The cross-in tray function is used to remove unwanted points in the 3D point cloud 700, such as points that are not part of the arc surface 112. Unwanted points may occur due to distortions caused by the lighting conditions or because the first stereo sensors 342 (and similarly for the second and third stereo sensors 344,346) have degraded over time. The unwanted points are removed by running optimizations on the bounding box created in the 3D point cloud 700 using the actual dimensions of the set of tyres 110. This optimizes the 3D image profile to be close to the real tyre surface for improved inspection of the set of tyres 110.

It will be appreciated various aspects of processing the stereo images of the tyre tread 120 and constructing the 3D image profile of the tyre tread 120 described above may apply similarly analogously for both single-tyre and multi-tyre configurations, as well as for constructing the 3D image profile of the sidewall 114.

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As shown in Figure 7A, as the arc surface 112 is curved, the 3D point cloud 700 constructed from the stereo images of the tyre tread 120 would have a significant surface curvature, especially if the first arm 332 actuates over a large angle around the arc surface 112. Constructing the 3D image profile of the tyre tread 120 may include executing an unwrapping or unrolling function 710 may be executed to flatten the 3D point cloud 700 and thereby construct the 3D image profile of the tyre tread 120. The unrolling function 710 includes steps of determining 3D quadrangles 720 from the 3D point cloud 700, mapping the 3D quadrangles 720 into a 3D plane, and forming a flattened 3D surface 730 from the 3D plane comprising the 3D quadrangles 720. The mapping of the 3D quadrangles 720 into the 3D plane may be performed using the Hoschek method (*Hoschek, Josef. – Approximation of surfaces of revolution by developable surfaces – Computer-Aided Design, Vol. 30, No. 10, 757-763, 1998* (incorporated in its entirety by reference herein)), specifically by rotating the 3D quadrangles 720 into the 3D plane. As shown in Figure 7B, each 3D quadrangle 720 may have the shape of a trapezium or more specifically an isosceles trapezium. Each 3D quadrangle 720 can be defined by four points in the 3D point cloud (p_0, p_1, p_2, p_3) together with four distances (d_1, d_2, d_3, d_4). d_1 is the distance between points p_2 and p_3 , d_2 is the distance between points p_1 and p_3 , d_3 is the distance between points p_0 and p_1 , and d_4 is the distance between points p_0 and p_2 . There is another distance d_5 between points p_0 and p_3 . Although the distances (d_1, d_2, d_3, d_4, d_5) are known, the three inner angles (α, β, γ) of the 3D quadrangle 720 are required to fully define it. The inner angles (α, β, γ) can be calculated according to the equations below.

$$\alpha = \arctan\left(\frac{r_1}{s_1 - d_5}\right)$$

$$\beta = 2\left(\arctan\left(\frac{r_1}{s_1 - d_4}\right) + \arctan\left(\frac{r_2}{s_2 - d_3}\right)\right)$$

$$\gamma = 2\arctan\left(\frac{r_2}{s_2 - d_5}\right)$$

$$s_1 = \frac{d_4 + d_1 + d_5}{2}$$

$$r_1 = \sqrt{\frac{(s_1 - d_4)(s_1 - d_1)(s_1 - d_5)}{s_1}}$$

$$s_2 = \frac{d_5 + d_2 + d_3}{2}$$

$$r_2 = \sqrt{\frac{(s_2 - d_5)(s_2 - d_2)(s_2 - d_3)}{s_2}}$$

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After obtaining the distances and inner angles of each 3D quadrangle 720, the 3D quadrangles 720 are continuously constructed and mapped into the 3D plane based on their neighbouring points, so that the neighbouring 3D quadrangles 720 align to each other in the 3D plane. The flattened 3D surface 730 is formed from the aligned
10 3D quadrangles 720 in the 3D plane. The unrolling function 710 further includes a step of constructing the 3D image profile of the tyre tread 120 from the flattened 3D surface 730.

It will be appreciated the unrolling function 710 may apply similarly analogously for
15 both single-tyre and multi-tyre configurations, such as the arc surfaces 112 of the outer tyre 110a and inner tyre 110b.

Figure 8A shows an example of the 3D image profile 800 of the tyre tread 120. A cross-section 802 of the 3D image profile 800 can be extracted to generate a 2D image
20 profile 804 of the cross-section 802. The 2D image profile 804 can be used to inspect the tyre tread 120 including tread depth at that cross-section 802. Through multiple cross-sections 802 of the 3D image profile 800, most of the arc surface 112 and the tyre tread 120 of the set of tyres 110 can be inspected along the width and radial direction thereof. The tread depth at every groove of the tyre tread 120 can be
25 measured from the cross-sections 802. Details such as the tread depth, tread pattern, and surface defects can be compared against the database 440 to evaluate any potential problems.

Figure 8B shows another example of the 3D image profile 800 in the form of a depth
30 map 810. The depth map 810 shows a colour distribution of the tread depths across

the arc surface 112. A cross-section 812 of the depth map 810 can be extracted to generate a 2D image profile 814 of the cross-section 812 to inspect the tyre tread 120 at that cross-section 812.

5 In some embodiments, the inspection robot 300 includes RGB sensors for capturing RGB images of the set of tyres 110 for inspecting the tyres 110 as well as for positioning the inspection robot 300 and aligning it to the tyres 110. The RGB sensors include a first RGB sensor aligned with the first stereo sensors 342 for capturing RGB images of the tyre tread 120. The RGB sensors may further include a second RGB
10 sensor aligned with the second stereo sensors 344 for capturing RGB images of the sidewall 114. The RGB sensors may further include a third RGB sensor aligned with the third stereo sensors 346 for capturing RGB images of the tyre tread 120 of the inner tyre 110b, wherein the first RGB sensor captures RGB images of the tyre tread 120 of the outer tyre 110a. The RGB sensors are aligned with the respective stereo
15 sensors 342,344,346 such that they can move together with the respective stereo sensors 342,344,346 by actuation of the respective arms 332,334.

Figure 8C shows a depth map 820 and a RGB image 830 of the tyre tread 120 of a new set of tyres 110. The grooves of the tyre tread 120 are clearly defined with
20 distinctly different tread depths from the other areas of the arc surface 112. The tread depth at each groove can be measured from the depth map 820. Comparatively, Figure 8D shows a depth map 840 and a RGB image 850 of the tyre tread 120 of an irregularly worn set of tyres 110, wherein the tyre tread 120 has a bald area 130. The bald area 130 is worn more extensively than other areas of the tyre tread 120 and it is
25 likely that human-based inspections would have missed this bald area 130 and passed this set of tyres 110. The tyre tread 120 has worn down until the grooves are no longer clearly defined. The depth map 840 shows that the bald area 130 has a smooth colour distribution, indicating that the bald area 130 no longer has grooves with deeper tread depth like those shown in the depth map 820. The depth maps 820,840 and RGB
30 images 830,850 can thus detect whether the set of tyres 110 is new or retreaded based on the number of grooves in the tyre tread 120.

The 3D image profile 800 and/or RGB images can be used to detect surface defects on the arc surface 112 of the set of tyres 110. For example, these surface defects can include foreign objects attached to the set of tyres 110, such as nails, stones, and dust coagulations, as well as surface damage like dents and punctures. The data
5 processing module 430 may be configured with suitable machine learning algorithms for detection of foreign objects. Particularly, the RGB images can be compared against reference images stored in the database 440, such as original wireframe diagrams of the tyres 110. From this comparison, foreign objects can be identified and analysed to evaluate the severity of each object and the risk of further damage to the tyres 110.

10 As described above, the second or lateral stereo sensors 344 are configured to capture stereo images of the sidewall 114 and a 3D image profile of the sidewall 114 can be constructed therefrom. The 3D image profile of the sidewall 114 allows for inspection of the tyre curvature, side bulging, and deformation pattern of the sidewall
15 114. For example, tyres 110 with the sidewall 114 being too flat or too bulging are not suitable for use. The 3D image profile and/or RGB images of the sidewall 114 can be used to detect damage on the sidewall 114, such as due to curbing of the tyres 110. Presence of foreign objects and/or curb defects can increase the risk of the tyre puncturing if these are not rectified timely.

20 In some embodiments as shown in Figure 9, the inspection system 200 further includes a surface pressure sensor 900 for measuring a footprint pressure of the set of tyres 110. The surface pressure sensor 900 includes a pressure sensing element 910 disposed between a pair of speed bumps 920 for stabilizing the set of tyres 110
25 on the pressure sensing element 910. The pressure sensing element 910 may include a set of piezoelectric pressure transducers to measure the footprint pressure. For example, surface pressure sensors 900 may be disposed at respective locations of the parking bay for the vehicle 100, each surface pressure sensor 900 for measuring the footprint pressure of a respective set of tyres 110 of the vehicle 100. When a set
30 of tyres 110 rolls over the speed bump 920 and onto the pressure sensing element 910, the piezoelectric pressure transducers deform and generate an electrical signal. The electrical signal is converted into a tyre footprint image profile representing the footprint pressure of the set of tyres 110. The footprint pressure of each set of tyres

110 of the vehicle can determine whether the set of tyres 110 is overinflated or underinflated. The footprint pressures of all the sets of tyres 110 of the vehicle 100 can determine whether the wheels and axles of the vehicle 100 are properly aligned.

5 The surface pressure sensor 900 is communicative with the computer system 400 and sends the tyre footprint image profile to the computer system 400 for inspection of the set of tyres 110. Like the inspection robot 300, the communication between the computer system 400 and the surface pressure sensor 900 may be wireless or wired.

10 In some embodiments, the data processing module 430 processes the 3D image profile of the sidewall 114 and the tyre footprint image profile to inspect the set of tyres 110. More specifically, the internal inflation pressure and internal temperature of the tyres 110 can be determined based on the tyre curvature, side bulging, and deformation pattern of the sidewall 114, as well as the footprint pressure.

15

In some embodiments, the data processing module 430 processes the 3D image profile of the tyre tread 120 and the tyre footprint image profile to inspect the set of tyres 110. More specifically, the severity of tyre baldness and the road-to-tyre grip efficiency can be determined based on the tread pattern and footprint pressure. The

20 road-to-tyre grip efficiency can be determined under different road conditions, such as hydroplaning under flooded road situations.

In some embodiments, the inspection robot 300 further includes a thermal sensor and a humidity sensor to measure the temperature and humidity of the ambient

25 environment. For example, the temperature and humidity levels in tropical climates can accelerate degradation of the rubber compound material used in the tyres 110 and worsens tyre wear. The data processing module 430 processes the temperature and humidity measurements together with other inspection factors described above to inspect the set of tyres 110.

30

The health condition of the set of tyres 110 can be inspected based on the various inspection modalities described above, including the 3D image profiles and RGB images of the tyre tread 120 and sidewall 114, as well as the footprint pressure and

ambient measurements like temperature and humidity. The results from these inspection modalities are compared against reference data in the database 440 to evaluate the tyres 110 and identify any potential problems or possible modes of failure. For example, the tyre tread 120 can be inspected, such as to determine surface wear condition and tread depth, by comparing the 3D image profile 800 against the database 440. The computer system 400 may include an alert notification module for raising alerts if the inspection results do not satisfy allowable conditions defined from the database 440. For example, alerts would be raised if the tread depth is below the allowable minimum limit, or if the internal inflation pressure exceeds a standard pressure range, or if foreign objects are detected on the tyres 110 which can puncture the tyres 110.

Additionally, the data processing module 430 may be configured to compute a wear index parameter based on these inspection modalities, wherein the wear index parameter provides an overall representation of the health condition of the set of tyres 110. The alert notification module 430 may raise alerts if the wear index parameter does not satisfy standard wear index parameters defined from the database 440.

The computer system 400 may include a user interface or dashboard for the operator or maintenance team in the inspection facility to read the inspection results and visualize the health condition of the tyres 110 in real time. The user interface also raises alerts to the operator if the inspection results show problems with the tyres 110. These alerts signal to the operator that there is potential tyre failure, and they should conduct further checks on the tyres 110 and take appropriate maintenance actions, such as repressurizing the tyres 110 or replacing the worn tyres 110 with new tyres 110. The worn tyres 110 may be disposed or scheduled for retreading. Once the operator acknowledges the alerts, the alerts may be logged in the database 440 for future reference, such as to revise safety protocols.

Different alerts may be raised for different levels of the tread depth. In one example, if the tread depth is below the allowable minimum limit of 4 mm (i.e. low tread depth), the alert informs the operator that the damage severity is high and the affected tyre 110 is not worthy for road operation. The tyre 110 with low tread depth cannot be

retreaded and must be replaced for safety reasons. If the tyre 110 continues to be used, accidents could happen and the bus operator could incur large operational costs. In another example, if the tread depth is above the allowable minimum limit but lower than that of a new tyre 110 (i.e. medium tread depth), the alert informs the operator

5 that the damage severity is medium and the affected tyre 110 can still be used for a predetermined number of days depending on the tread depth, wherein this number of days is calculated based on historical tread depth data of the same type of tyre 110 from the database 440. The operator should schedule the tyre 110 for retreading before this predetermined number of days expire.

10 The data processing module 430 may also upload the inspection results for the current set of tyres 110 into the database 440 and record them against details of the vehicle 100 and tyres 110, such as the vehicle make, wheel axle and type position details. Inspection results for multiple tyres 110 of multiple vehicles 100 can be accumulated in the database 440 and this data can be used to complement tyre manufacturer

15 guidelines and improve the standard reference data. Further, the data can be used to generate a training dataset for machine learning purposes that can improve tyre inspections in future.

Therefore, the inspection system 200 described herein provides a highly accurate and

20 repeatable way of inspecting the tyres 110 without human interference which would have greater likelihood of inspection errors. The inspection system 200 can identify any issues with the tyres 110 so early preventive measures can be taken, otherwise these issues can potentially cause catastrophic damage to the tyres 110 or even road accidents if the defective tyres 110 continue to be used.

25 The inspection system 200 is useful for a bus operator with a large fleet of buses. The inspection results obtained by the inspection system 200 ensure that the bus tyres 110 are within reasonable operational and safety limits. If a set of tyres 110 is found to be defective, such as having low tread depths, the bus operator can take timely

30 preventive actions such as to send the tyres 110 for retreading which would improve the operational lifespan of the tyres 110. Retreading the tyres 110 reduces the operational cost for the bus operator compared to replacing the tyres 110, which might

have happened if the defective tyres 110 continue to be used and become permanently damaged.

5 Having a fleet of buses with good useable tyres 110 improves fuel efficiency and reduces labour and maintenance costs in the long run. There is also lower risk of vehicle downtime or unwanted stoppages, which would inconvenience passengers and affect the commercial revenue of the bus operator. Moreover, collective inspection results for the tyres 110 of all their buses can provide valuable information and insights to the bus operator and relevant stakeholders, such as investors, to make business
10 decisions such as on future improvements of the bus systems.

Some non-limiting examples of the computer system 400 include computers, laptops, mini-computers, mainframe computers, any non-transient and tangible machines that can execute a machine-readable code, cloud-based servers, distributed server
15 networks, and a network of computer systems. As used herein, a server is a physical or cloud data processing system on which a server program runs. The server may be implemented in hardware or software, or a combination thereof. Additionally, the computer system 400 includes a processor, a memory, and various other modules or components. The modules and components thereof are configured for performing
20 various operations or steps and are configured as part of the processor. Such operations or steps are performed in response to non-transitory instructions operative or executed by the processor. The memory is used to store instructions and perhaps data which are read during program execution. The memory may be referred to in some contexts as computer-readable storage media and/or non-transitory computer-
25 readable media. Non-transitory computer-readable media include all computer-readable media, with the sole exception being a transitory propagating signal per se.

In the foregoing detailed description, embodiments of the present disclosure in relation to an inspection system, method, and robot for inspecting tyres of a vehicle are
30 described with reference to the provided figures. The description of the various embodiments herein is not intended to call out or be limited only to specific or particular representations of the present disclosure, but merely to illustrate non-limiting examples of the present disclosure. The present disclosure serves to address at least

one of the mentioned problems and issues associated with the prior art. Although only some embodiments of the present disclosure are disclosed herein, it will be apparent to a person having ordinary skill in the art in view of this disclosure that a variety of changes and/or modifications can be made to the disclosed embodiments without
5 departing from the scope of the present disclosure. Therefore, the scope of the disclosure as well as the scope of the following claims is not limited to embodiments described herein.

Claims

1. An inspection robot for inspecting tyres of a vehicle, the inspection robot comprising:
 - 5 a chassis body comprising a driving mechanism for driving the inspection robot;
 - a robotic arm assembly coupled to the chassis body for actuating around a set of tyres of the vehicle, the robotic arm assembly comprising:
 - a first arm actuable around an arc surface of the set of tyres,
 - 10 the arc surface comprising a tyre tread; and
 - a second arm coupled to the first robotic arm and actuable around a sidewall of the set of tyres; and
 - first stereo sensors moveable by the first arm around the arc surface for capturing stereo images of the tyre tread,
 - 15 wherein a 3D image profile of the tyre tread is constructable from the stereo images of the tyre tread for inspection of the tyre tread.
2. The inspection robot according to claim 1, further comprising second stereo sensors moveable by the second arm around the sidewall for capturing stereo images
20 of the sidewall, wherein a 3D image profile of the sidewall is constructable from the stereo images of the sidewall for inspection of the sidewall.
3. The inspection robot according to claim 1 or 2, further comprising third stereo sensors moveable by the first arm around the arc surface of the set of tyres for
25 capturing stereo images of the tyre tread of the set of tyres.
4. The inspection robot according to claim 3, wherein the first and third stereo sensors are moveable by the first arm around the arc surface of an outer tyre and an inner tyre, respectively, of the set of tyres for capturing stereo images of the tyre tread
30 of the outer tyre and inner tyre, respectively.
5. The inspection robot according to any one of claims 1 to 4, further comprising RGB sensors for capturing RGB images of the set of tyres.

6. An inspection method for inspecting tyres of a vehicle, the inspection method comprising:
- 5 driving an inspection robot towards the vehicle, the inspection robot comprising a robotic arm assembly for actuating around a set of tyres of the vehicle;
- actuating a first arm of the robotic arm assembly around an arc surface of the set of tyres, the arc surface comprising a tyre tread;
- 10 actuating a second arm of the robotic arm assembly around a sidewall of the set of tyres, the second arm coupled to the first arm;
- moving, by the first arm, first stereo sensors around the arc surface; and capturing, using the first stereo sensors, stereo images of the tyre tread, wherein a 3D image profile of the tyre tread is constructable from the stereo images of the tyre tread for inspection of the tyre tread.
- 15
7. The inspection method according to claim 6, further comprising:
- moving, by the second arm, second stereo sensors around the sidewall; and
- 20 capturing, using the second stereo sensors, stereo images of the sidewall,
- wherein a 3D image profile of the sidewall is constructable from the stereo images of the sidewall for inspection of the sidewall.
8. The inspection method according to claim 6 or 7, further comprising:
- 25 moving, by the first arm, third stereo sensors around the arc surface of the set of tyres; and
- capturing, using the first and third stereo sensors, stereo images of the tyre tread of the set of tyres.
- 30 9. The inspection method according to claim 8, comprising:
- moving, by the first arm, the first and third stereo sensors around the arc surface of an outer tyre and an inner tyre, respectively, of the set of tyres; and

capturing, using the first and third stereo sensors, stereo images of the tyre tread of the outer tyre and inner tyre, respectively.

10. A computer system for inspecting tyres of a vehicle, the computer system
5 comprising:
- a transceiver module configured for receiving, from an inspection robot configured for inspecting the vehicle, stereo images of a tyre tread around an arc surface of a set of tyres of the vehicle;
 - an image processing module configured for constructing a 3D image
10 profile of the tyre tread from the stereo images of the tyre tread; and
 - a data processing module configured for inspecting the set of tyres by comparing the 3D image profile of the tyre tread against a database.
11. The computer system according to claim 10, wherein:
- 15 the transceiver module is configured for receiving, from the inspection robot, stereo images of a sidewall of the set of tyres;
 - the image processing module is configured for constructing a 3D image profile of the sidewall from the stereo images of the sidewall; and
 - the data processing module is configured for inspecting the set of tyres
20 by comparing the 3D image profile of the sidewall against the database.
12. The computer system according to claim 10 or 11, wherein:
- the transceiver module is configured for receiving, from a surface pressure sensor configured for measuring a footprint pressure of tyres, a tyre
25 footprint image profile representing the footprint pressure of the set of tyres;
 - and
 - the data processing module is configured for processing the tyre footprint image profile and the 3D image profile of the tyre tread to inspect the set of
30 tyres.
13. The computerized system according to claim 12, wherein the data processing module is configured for processing the tyre footprint image profile and a 3D image profile of a sidewall of the set of tyres to inspect the set of tyres.

14. A computerized method for inspecting tyres of a vehicle, the computerized method comprising:
- receiving, from an inspection robot configured for inspecting the vehicle,
5 stereo images of a tyre tread around an arc surface of a set of tyres of the vehicle;
 - constructing a 3D image profile of the tyre tread from the stereo images of the tyre tread; and
 - 10 inspecting the set of tyres by comparing the 3D image profile of the tyre tread against a database.
15. The computerized method according to claim 14, wherein constructing the 3D image profile of the tyre tread comprises:
- calculating a set of disparity maps from the stereo images of the tyre
15 tread; and
 - constructing a set of 3D point clouds from the disparity maps;
 - merging the 3D point clouds to form a merged 3D point cloud; and
 - constructing the 3D image profile of the tyre tread from the merged 3D
20 point cloud.
16. The computerized method according to claim 15, wherein constructing the 3D image profile of the tyre tread further comprises:
- denoising the merged 3D point cloud and/or each 3D point cloud in the
set of 3D point clouds; and/or
 - 25 executing an unrolling function to flatten the merged 3D point cloud and
thereby construct the 3D image profile of the tyre tread,
wherein the unrolling function optionally comprises:
 - determining 3D quadrangles from the merged 3D point cloud;
 - mapping the 3D quadrangles into a 3D plane;
 - 30 forming a flattened 3D surface from the 3D plane comprising the
3D quadrangles; and
 - constructing the 3D image profile of the tyre tread from the
flattened 3D surface.

17. The computerized method according to any one of claims 14 to 16, wherein said inspecting of the tyres comprises detecting surface defects on the arc surface of the tyres, the surface defects optionally comprising foreign objects.
- 5
18. The computerized method according to any one of claims 14 to 17, further comprising raising alerts inspection results from the inspection of the tyres do not satisfy allowable conditions defined from the database.
- 10
19. An inspection system for inspecting tyres of a vehicle, the inspection system comprising:
- an inspection robot comprising:
 - a chassis body comprising a driving mechanism for driving the inspection robot;
 - 15 a robotic arm assembly coupled to the chassis body for actuating around a set of tyres of the vehicle, the robotic arm assembly comprising:
 - a first arm actuatable around an arc surface of the set of tyres, the arc surface comprising a tyre tread; and
 - a second arm coupled to the first robotic arm and
 - 20 actuatable around a sidewall of the set of tyres; and
 - first stereo sensors moveable by the first arm around the arc surface for capturing stereo images of the tyre tread; and
 - a computer system communicative with the inspection robot, the computer system comprising:
 - 25 a transceiver module configured for receiving the stereo images of the tyre tread from the inspection robot;
 - an image processing module configured for constructing a 3D image profile of the tyre tread from the stereo images of the tyre tread; and
 - a data processing module configured for inspecting the set of tyres by
 - 30 comparing the 3D image profile of the tyre tread against a database.
20. The inspection system according to claim 19, further comprising a surface pressure sensor configured for:

measuring a footprint pressure of the set of tyres,
generating an electrical signal based on the footprint pressure;
converting the electrical signal into a tyre footprint image profile
representing the footprint pressure of the set of tyres; and
5 sending the tyre footprint image profile to the computer system.