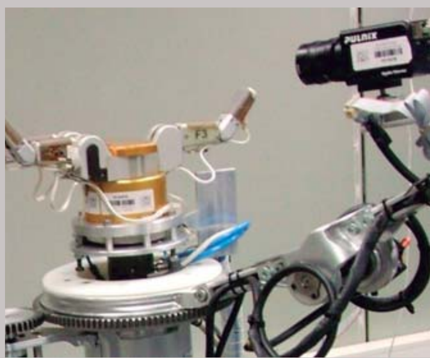
JNR2019

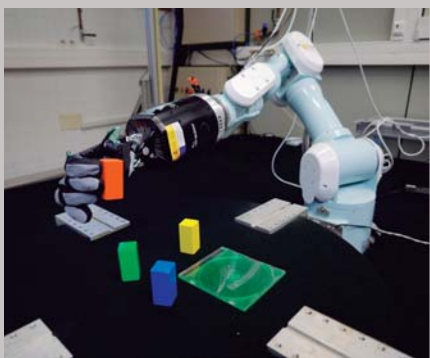
Jornadas Nacionales de Robótica

Spanish National Robotics Conference

LIBRO DE ACTAS

Alicante, SPAIN - June 13th-14th, 2019






CEA Robótica

Universitat d'Alacant
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Robotnik

ABB

UNIVERSITAS Miguel Hernández

CFZ Cobots

GOBIERNO DE ESPAÑA
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IEEE Robotics & Automation Society Spanish Chapter

JNR2019

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Spanish Robotics Conference

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Organizado por:

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PREFACIO

A través de estas páginas, queremos dar la bienvenida a todos los asistentes de las Jornadas Nacionales de Robótica de 2019. Son varias ya las ediciones que se vienen realizando de este evento lo que sin duda afianza el carácter de este que poco a poco se consolida como un referente donde investigadores y universitarios relacionados con el mundo de la robótica tienen un punto de encuentro en el que discutir temas relacionados con esta temática. Como organizadores de este evento, durante varios meses hemos intentado que la organización de las diferentes actividades posibilite un marco donde todos los asistentes puedan aprovechar todas y cada una de las actuaciones programadas. A diferencia de otras ediciones, en esta anualidad se ha querido incrementar el tipo de resultados que se presentan en la misma, facilitando en todo momento la difusión de resultados y actividades realizadas en los últimos meses por los diferentes miembros y grupos de investigación. En definitiva, queremos que estas Jornadas propicien un punto de encuentro para todos los investigadores donde compartir avances, resultados y trabajos futuros de la robótica en España. En conjunto, y gracias a todas las actividades propuestas, se presentarán durante las jornadas un total de 36 comunicaciones. Un número muy elevado de trabajos que sin duda alguna muestran el alto interés de las jornadas entre toda la comunidad científica. Estas comunicaciones se organizan en dos sesiones de comunicaciones, en las que cada uno de los trabajos contarán con 5 minutos de exposición y un turno final de discusión.

Una de las señas de identidad de las Jornadas Nacionales de Robótica en sus distintas ediciones consiste en contar con prestigiosos investigadores europeos. En esta ocasión se cuenta con dos conferenciantes de prestigio. En la primera de estas sesiones plenarias organizadas, tendrá lugar la conferencia “Is this my body? Neuro-inspired robotic body perception and action”, impartida por Pablo Lanillos, del Institute of Cognitive Systems (ICS) perteneciente a la Technical University of Munich (TUM). En la segunda de las sesiones plenarias, se impartirá la conferencia “Robot visión for the perception of Objects” a cargo de Markus Vincze del Vision for Robotics (V4R) dentro del Automation and Control Institute (ACIN) de la Technical University of Wien (TUW). Sin duda alguna estos prestigiosos conferenciantes atraerán el interés de todos los asistentes.

Además de las comunicaciones presentadas por parte de los asistentes a las Jornadas, así como de las conferencias invitadas, se quiere contar en todo momento con las principales novedades de las empresas relacionadas con la robótica en España. En este sentido, dentro de una de las actividades se ha programado una sesión en la que diferentes empresas (Universal Robots, CFZ Cobots, Robotnik Automation SLL y ABB) presentarán algunos de los últimos desarrollos relacionados con la robótica colaborativa y la industria 4.0.

Además de estas actividades, tendrá lugar una reunión informativa en la que algunas de las entidades y sociedades españolas relacionadas con la robótica mostrarán las diferentes actuaciones llevadas a cabo por estas (EuRobotics, IROS, European Robotics Forum, IEEE Student Branch, …).

Dentro del programa planificado se integran además una comida de trabajo, 2 pausas para café y una cena en la que todos los asistentes podrán continuar compartiendo las experiencias, tendencias y trabajos desarrollados en las diferentes actividades.

Por último, quisiéramos agradecer el apoyo recibido para la organización y celebración de estas Jornadas. En primer lugar, a las dos universidades que organizan y soportan las mismas, la Universidad de Alicante y la Universidad Miguel Hernández de Elche, y en especial a los miembros de ambas universidades que han participado muy activamente en su organización. A la Red Nacional de Robótica por su inestimable colaboración y ayuda en la realización de algunas de las actividades propuestas, así como en el soporte prestado. A la sección del IEEE RAS Spanish Chapter, que ha posibilitado que uno de los conferenciantes invitados pueda acudir a las Jornadas. Como patrocinadores se cuenta con el apoyo de diferentes empresas relacionadas con la robótica (ABB, Robotnik y CFZ Cobots). Desde el primer momento que tuvieron conocimiento de estas, se han prestado en todo momento a apoyar las mismas. Finalmente, y quizás más importante a todos los asistentes a las Jornadas, ya que, sin su presencia y actividad, estas carecerían de sentido.

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Trajectory Planning for MASAR: a New Modular and Single-Actuator Robot

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Abstract

Single-actuator mobile robots have the benefits of low energy consumption, low weight and size, and low cost, but their motion is typically only one-dimensional. By using auxiliary binary mechanisms that redirect and channel the driving force of their only actuator in different ways, it is possible for these robots to perform higher-dimensional motions (walk straight, turn left/right, jump...). This paper presents the MASAR, a new Modular And Single-Actuator Robot that carries a single motor and several adhesion pads. By alternately attaching these adhesion pads to the environment or detaching them, the proposed robot is able to pivot about different axes using only one motor, with the possibility of performing concave plane transitions or combining with other identical modules to build more complex reconfigurable robots. In this paper we solve the planar trajectory planning of this robot for polygonal paths made up of sequences of segments, which may include narrow corridors that are difficult to traverse. *Copyright* © CEA.

Keywords:
Single-Actuator Robots, Trajectory Planning, Climbing Robots, Modular Robots, Alternating pivot, Adhesion pads

1. Introduction

Single-Actuator Mobile Robots (SAMR) are robots with the ability to explore environments with relatively high freedom using only one motor. The most direct consequences and advantages of using a single actuator are savings in costs, energy consumption, size, and weight. Due to these advantages, SAMR robots are especially appropriate for applications that require energy autonomy, miniaturization, and navigation in difficult-to-access areas, with the purpose of performing inspection, cleaning, reconnaissance or search-and-rescue tasks, among others (Zarrouk and Fearing, 2015).

Most SAMR robots reported in the specialized literature can be classified into one of three main types (type-I, type-II, or type-III), depending on two criteria: the dimension of their workspace, and the existence of auxiliary binary mechanisms that help the robot to change the direction of motion. This proposed classification is illustrated in Figure 1.

Type-I SAMR are robots that use a single actuator to control their motion along a one-dimensional workspace, with no additional mechanisms. For example, Soyguder and Alli (2011) present an octopod that can walk forward or backwards along a straight line by means of a single motor and a system of cams that synchronize the motion of all its eight legs. Similarly, Choi et al. (2015) and Birkmeyer et al. (2011) present two climbing robots that can vertically climb using a single actuator each. Zarrouk et al. (2016) present a robot that can climb or move along a straight line by using a wave-like locomotion generated by a single motor. Type-I SAMR robots can only move along one dimension. In order for these robots to be able to change the direction of their motion and control their motion in higher-dimensional workspaces (e.g., plane or space), it would be necessary to equip them with additional motors (Birkmeyer et al., 2011; Zarrouk et al., 2016), and thus they would no longer be single-actuator mobile robots.

According to Figure 1, type-II SAMR have workspaces with dimension higher than one, i.e., they are not constrained to move only along a straight line, but can typically control their position and orientation in a plane. In addition to having a main *continuous* actuator, type-II SAMR are characterized by having also some additional binary mechanisms that allow the robot to modify its topology, changing in this way the effect that its single main actuator exerts on the overall motion of the robot. In other words: strictly speaking, type-II SAMR robots should be called "Single-Actuator Mobile Robots… *with auxiliary binary actuators*". Thanks to these auxiliary binary actuators, the driving force generated by the only continuous actuator of the robot can be channeled as required,

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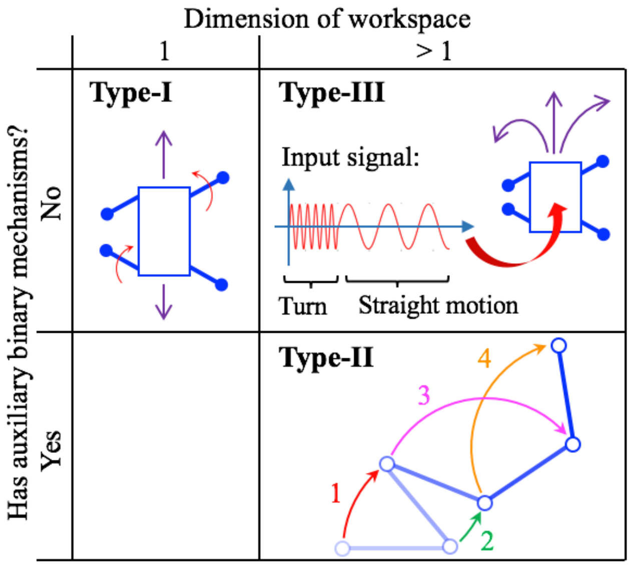

Figure 1: Classification of Single-Actuator Mobile Robots.

e.g., to produce straight motion, to change the direction of motion, to jump, etc. Note that these auxiliary binary actuators do not necessarily need to be motors or actuators in the usual sense of the term, but they can simply be electromagnets, suction cups, or clutches that engage or disengage two mobile parts of some internal mechanism of the robot, in order to transmit the driving force of the only continuous actuator to different mechanisms and modify the overall motion of the mobile robot.

Some examples of type-II SAMR robots can be found in the literature. For example, Sfeir et al. (2014) present a mobile robot with two variable-radius wheels driven by a single motor such that, when activating a clutch, this motor also displaces the center of mass of the robot along its main shaft, which modifies the relative radii of the wheels and produces a change in the direction of motion due to differential drive kinematics. Cheng et al. (2010) propose a snake-like robot powered by a single tendon-driven actuator. This robot is made up of several segments rigidly connected by welded joints such that, when applying an electric current to some of these welds, they can temporarily melt in order to modify the geometry of the robot. By selectively melting these welded joints and actuating its only motor, this robot can move along straight lines or change its direction in a plane. Finally, Hoover et al. (2010) present the DynaRoACH robot, which is inspired by cockroaches and has a single actuator to move along straight lines. This robot can also turn by modifying the relative stiffness of its legs through shape-memory alloys.

Type-III SAMR typically are under-actuated mobile robots that use a single actuator and lack auxiliary binary mechanisms, and they are able to control their motion in more than one dimension. Usually, these robots will perform some type of motion or other (e.g., moving along a straight line, turning, jumping...) depending on the characteristics (amplitude, sign, frequency...) of the input signal applied to its only actuator. For example: Refael and Degani (2015) present a robot that swims over water surfaces, this robot is driven by a single actuator that produces straight motion when excited at constant frequency, whereas it modifies the direction of motion when being excited at different frequencies during each semi-period. Dharmawan et al. (2017) developed a micro-robot made up of a single piezoelectric actuator that makes the robot move in straight lines or turn left/right depending on the natural frequency at which this actuator is excited. Zarrouk and Fearing (2015) present a single-actuated hexapod robot whose legs have different stiffnesses; this robot will walk in straight lines or turn depending on the shape of the velocity profile introduced to its only motor. Ho and Lee (2012) proposed a robot consisting of a single large wheel with only one motor: if this motor oscillates between two limit positions, the robot rolls along a straight line. If the motor overcomes one of such limits, then a spring is compressed and its elastic energy is suddenly released, which produces the jump of the robot to overcome steps and other obstacles. Finally, Zhao et al. (2013) present a jumper robot that can perform three different movements using only one motor: jumping (by compressing a spring), standing up after the jump, and modifying the direction of the next jump. This robot will perform one motion or the other depending on the amplitude and sign of the rotation of the motor.

Comparing the three types of SAMR robots identified, generally one of the main drawbacks of type-III SAMR is that it may be difficult to precisely control their motion (Zarrouk and Fearing, 2015), since it largely depends on their under-actuated dynamics. On the contrary, it is relatively easy to precisely control the motion of type-II SAMR robots by using their auxiliary binary actuators. Type-I robots are usually simpler but they can only move along one dimension. Note that one of the cells in the table of Figure 1 is empty because it would not make much sense to design SAMR robots that have auxiliary binary mechanisms but can only move along one-dimensional workspaces (the purpose of these binary mechanisms is precisely to increase the dimension of the workspace).

Acknowledging the higher simplicity and flexibility of type-II SAMR robots, this paper presents MASAR: a new Modular And Single-Actuator Robot that explores two-dimensional environments by rotating about binary pivots that are alternately adhered to the environment or detached as required. Contrary to previous type-II SAMR, the proposed robot is capable of performing concave transitions between orthogonal planes, which makes it especially suitable for exploring indoor environments delimited by floors, walls, and ceilings. This paper focuses on the trajectory planning of the proposed robot, in order to follow polygonal paths composed of chains of straight segments that may include narrow sections that constrain the movement of the robot.

This paper is organized as follows. First, Section 2 presents the proposed MASAR robot. Then, Section 3 solves its path planning problem in the case of polygonal paths with narrow sections that must be traversed. Next, Section 4 illustrates the proposed path planning solution with some examples. Finally, Section 5 presents the conclusions and future work.

2. MASAR: a New Modular And Single-Actuator Robot

This section presents a new type-II SAMR robot, whose trajectory analysis is the main focus of the present paper. This robot (patent no. ES2684377, with priority date 2017-03-31) is depicted in Figure 2, and it has been called MASAR, which is the acronym of “Modular And Single-Actuator Robot”.

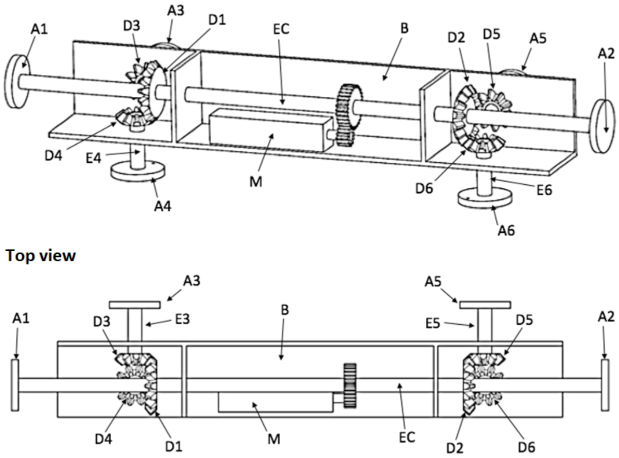

Figure 2: MASAR, a Modular And Single-Actuator Robot

As illustrated in Figure 2, MASAR has a main body B rigidly attached to a single motor M that drives a central shaft EC that can rotate with respect to body B. At each side of the motor M, there is a mechanism comprised of three bevel gears with mutually orthogonal and intersecting axes: gears {D1, D3, D4} to the left of M, and gears {D2, D5, D6} to the right. Gears {D3, D4, D5, D6} are connected to respective small shafts {E3, E4, E5, E6} that can rotate with respect to the main body B, these axes have adhesion pads {A3, A4, A5, A6} at their ends (see Figure 2). Likewise, the central shaft EC has adhesion pads {A1, A2} at both ends.

According to the classification of Figure 1, MASAR is a type-II SAMR robot because it has several binary adhesion pads (A1, A2, A3…) each of which may be ON or OFF (i.e., adhered to the environment or not adhered to it, respectively). The locomotion of this robot is as follows. Assume that the robot is initially resting on the floor through pads A4 and A6, as in the previous Figure 2. Assume also that only pad A4 is ON (i.e., adhered to the floor). When actuating motor M in this situation, since A4 is rigidly adhered to the floor, the central shaft EC (and the whole robot, as a consequence) will rotate about the axis of E4, since bevel gear D1 will roll on gear D4, which is static because A4 is adhered to the floor. This motion is illustrated in Figure 3a, which represents schematically a top view of the robot. After rotating the robot about E4, the adhesion pad A6 would be turned ON whereas A4 would be turned OFF, and powering the motor in that case would produce the rotation of the whole robot about axis E6, as indicated in Figure 3b. By alternately turning ON and OFF pads A4 and A6, the robot would walk on the floor following any desired trajectory (se Figure 3c or Figure 1).

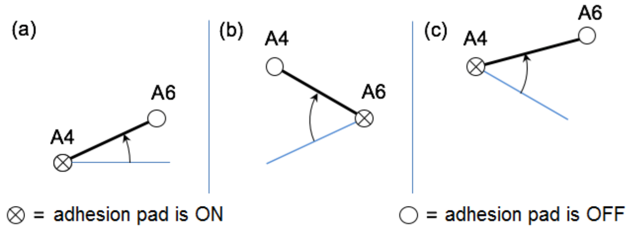

Figure 3: Locomotion of the MASAR robot.

A similar robot that also uses this mode of locomotion was developed by Mir-Nasiri et al. (2018) for autonomous cleaning of glass windows. In their robot, two opposite pads similar to our pads A4 and A6 are simultaneously powered by the same motor by means of a belt mechanism, whereas our robot uses the bevel-gear mechanisms depicted in Figure 2. Besides this, our robot has two main differences with respect to the one described in (Mir-Nasiri et al., 2018):

- MASAR can perform concave plane transitions, such as those necessary for traversing between a vertical wall and the floor/ceiling or between different walls. This is thanks to the arrangement of adhesion pads at orthogonal faces of our robot (see Figure 4). Accordingly, this allows MASAR to climb walls and autonomously explore three-dimensional environments made up of the concave intersection of orthogonal planes (such as indoor environments delimited by walls, ceilings and floors) using only one motor.
- Our robot is modular, in the sense that several identical MASAR modules can be combined (joining their adhesion pads) in order to form multi-degree of freedom manipulators able to complete tasks more complex than a single module can complete. This idea is illustrated in Figure 5, which shows a team of four MASAR modules working together to form a serial arm that can climb to a table. Note that a single module would be unable to climb the table on its own, since this would require a convex transition between the table leg and the tabletop, which a single module cannot perform.

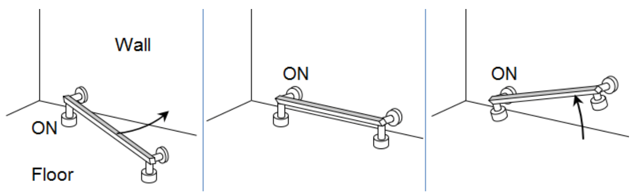

Figure 4: a MASAR robot performing a concave plane transition.

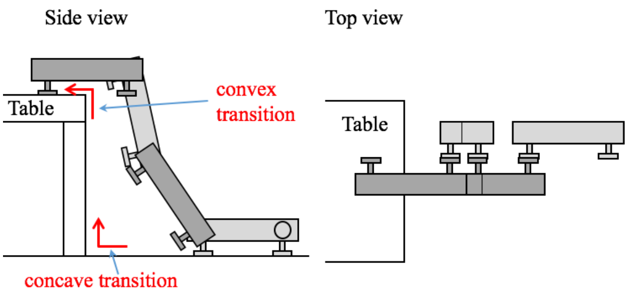

Figure 5: four MASAR modules combined for climbing a table.

3. Trajectory Planning

This section approaches three planar trajectory planning problems of the proposed robot. Assuming that the trajectory to follow is polygonal, made up of a sequence of segments obtained from, e.g. an A* algorithm, the problems to solve are the following:

1) How to make the robot to follow a polygonal path without obstacles that constrain the motion of the robot, i.e., there is no restriction on the amplitude of the rotations that the robot can perform.
2) How to make the robot go through a narrow path or strait, which restricts the amplitude of its rotations.
3) Combination of both previous problems, solving a set of segments which may contain straits.

These three problems will be geometrically solved in following sections.

3.1. Problem 1: Following Unconstrained Polygonal Paths

The first decision to make is the gait that the robot should use for following straight trajectories that have no restrictions, that is, paths with no obstacles or collisions that may constrain the amplitude of the robot's rotations (at most, only changes of direction are found). If the motion of the robot is not constrained, then the most reasonable gait for the robot should be based on 180º turns, since they achieve a maximum step along the trajectory and reduce overall time. This is illustrated in Figure 7, and will be further discussed in Section 4.1.

We assume that, at the beginning of the polygonal path, the robot starts with any orientation, and with its middle point placed on the first straight segment of the path. If this was not the case, it will simply be necessary to rotate the robot around any of its pivots until its middle point intersects this segment.

To start the movement that travels each segment using 180º turns, the robot must be completely aligned with the straight line. If we had a situation where none of both pivots are initially on the line, two turns are required for reaching the desired position, as explained next.

3.1.1. Initial Reorientation

As mentioned before, initially it may be possible that both pivots are not on the line; the robot must re-orient itself to line up with the straight line, with its both pivots on it. Two turns will be needed, as illustrated in Figure 6.

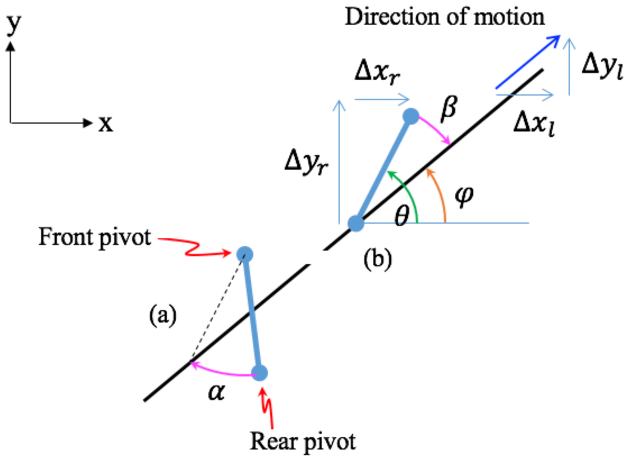

Figure 6: Initial reorientation for aligning the robot with the first segment of a polygonal path.

First turn, considered as initial re-orientation and illustrated in Figure 6a, is based on the search of a point on the line whose distance to front pivot is equal to robot's length. This point is found solving the intersection between the line and the circle centered at the front pivot and with radius equal to the length of the robot.

Once found, through the law of cosines, we calculate the value of the angle α which allows us to place the rear pivot on the line. Considering the straight line as a vector, and being its end the goal for our robot, if turning pivot is located on the right of this vector, the angle calculated will be positive (counter-clockwise). Otherwise, it will be negative (clockwise), as in Figure 6a.

Final re-orientation, shown in Figure 6b, departs from previous situation, and will be done taking as turning pivot the rear one, which is already on the line. The angle to rotate the robot is:

$$\beta = \theta - \varphi \tag{1}$$

where θ is the orientation of the robot and φ is the orientation of the line (with respect to the horizontal x axis). Both angles are calculated considering both the line and the robot as vectors, and using **atan2** function, which provides the angle between a vector and the horizontal axis:

$$\theta = \mathrm{atan2}(\Delta y_r\,, \Delta x_r) \tag{2}$$

$$\varphi = \mathrm{atan2}(\Delta y_l, \Delta x_l) \qquad (3)$$

3.1.2. Straight Motion and Change of Direction

When the robot is completely on the line, movement along it can be initialized. As we previously argued, this movement is based on 180º turns, alternating pivot and angle sign:

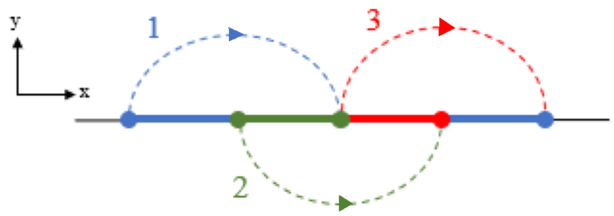

Figure 7: Gait of the robot by turning 180º each step.

After performing a certain number of movements, when the distance from the front pivot to the end of the current line is below a prefixed threshold, the robot must stop its advance (considering that it has reached the end of the line) and starts a sequence of movements for moving to the next straight line:

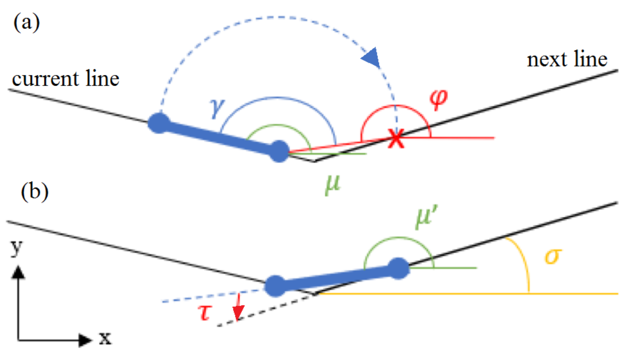

Figure 8: Change of direction and reorientation.

The first of these movements achieves placing the rear pivot of the robot on the next line (Figure 8a). This is done looking for a point of the next straight line whose distance to robot's front pivot is equal to robot's length. Again, this consists in solving the intersection between a straight line and a circle centered at the front pivot and with robot's length as radius, as in Figure 6a.

Once the intersection point is found, a virtual vector is defined from this intersection point to the front pivot of the robot, and φ is the angle that this vector forms with the horizontal axis. Moreover, we also calculate the angle that the robot forms with the horizontal axis, it is called μ. After that, the final angle γ we need for placing the rear pivot at the intersection point is:

$$\gamma = \varphi - \pi - \mu \qquad (4)$$

Finally, for placing the robot fully on the new line, we must rotate the robot around its front pivot by the following angle (see Figure 8b):

$$\tau = \pi - (\mu' - \sigma) \qquad (5)$$

being μ' the new angle obtained between the robot and the horizontal axis, and σ an angle between the new line and the horizontal axis.

When this change of direction is over, our robot will be able to continue along the new line with the described locomotion: performing 180º turns until the end of the new line is reached, then changing again the direciton of motion, etc., until the end of the whole polygonal path is reached.

3.2. Problem 2: Traversing Narrow Segments or Straits

This section is focused on solving some situations where the robot needs to go through a narrow path, namely, a straight path bounded by two walls (see Figure 9). In this case, the motion defined in the previous section is not suitable, since rotations as wide as 180º are not possible inside the strait.

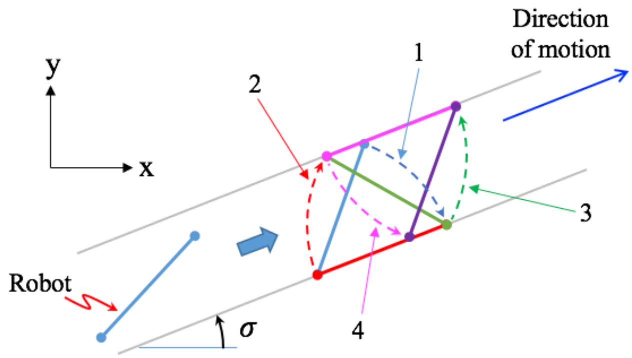

Figure 9: Traversing a narrow path.

For solving narrow path locomotion, next we will assume that this occurs in a horizontal path. If the robot finds a narrow path forming some angle σ with the horizontal axis, then it would be only necessary to rotate the problem by an angle $-\sigma$, solve it the way it will be explained in this section, and finally restore the solution to its original orientation (again, rotating all elements by an angle σ).

3.2.1. Initial Maneuvering Inside the Strait

The faster and more efficient motion for going through a narrow path is the one in which the robot moves by placing its whole body alternately on each wall, as illustrated in Figure 9. This motion is the best option due to the achievement of a maximum advance through the narrow path. For achieving this motion, the robot must start this movement with each pivot placed at each wall.

The main objective of this sub-section is to calculate the pair of angles that the robot has to rotate (each rotation about a different pivot) to reach the desired initial position.

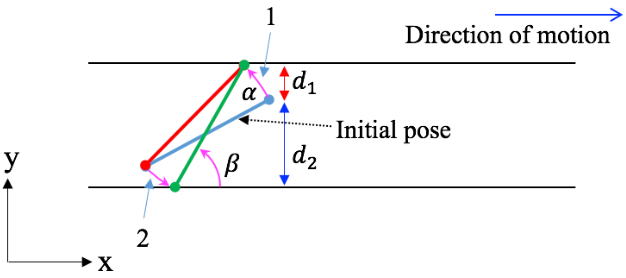

Figure 10: Placing each pivot on a different wall.

This process begins by looking for the shortest distance $\min\{d_1, d_2\}$ from each wall to the front pivot of the robot:

$$d_i = \frac{|a_i \cdot x_{front} + b_i \cdot y_{front} + c_i|}{\sqrt{a_i^2 + b_i^2}} \quad (6)$$

where each wall $i = \{1,2\}$ is defined by its implicit equation $a_i x + b_i y + c_i = 0$. Once the calculation is done, a comparison is required for taking the shortest of both calculated distances. The chosen one indicates on which wall to place the front pivot.

Once the nearest line is known, we must find again the point on this line whose distance to the rear pivot is equal to the length of the robot, as in Figures 6a and 8a. This point is found solving the intersection between the line and a circle with radius equal to the length of the robot and centered at the rear pivot. After obtaining this intersection point, the law of cosines is applied for obtaining the desired angle α that the robot must be rotated about the rear pivot in order to place the front pivot at the calculated intersection point.

When this point is reached by the front pivot, the same process needs to be done again for placing the rear pivot on the opposite wall, this time taking as axis of rotation the front pivot.

3.2.2. Movement Along the Strait

After reaching the desired initial situation, the robot proceeds to move along the strait, until reaching its end. This movement is accomplished by rotating always the same angle β, which is the angle between the robot and the walls when the robot has each pivot placed on a different wall, as indicated in Figure 10. As explained before, this is the optimal rotation for advancing along the strait since it produces the maximum advancement along the direction of the strait in a single step.

This angle is calculated using Equation (1), i.e., doing the subtraction of the angle between the robot and the horizontal axis, and between any wall and the horizontal axis. Then, the robot needs to alternate its turning pivot and the angle sign in every step. It will go forward, placing itself on the walls alternately, as illustrated in Figure 9.

3.3. Problem 3: Combination of Both Problems

After explaining the previous two problems, this section analyzes the possibility of combining both cases.

This combination is based on an online management by the robot while moving, i.e., as it proceeds along its travel, if the robot finds a strait, a change of direction, or unconstrained 180º movements along a line, it will perform some or other of the relevant actions defined in previous subsections.

At this point, it is also important to take into account how the robot is able to face straits, that is, how it enters and leaves them.

Taking as starting point any strait, for solving this situation, we have opted for defining a virtual narrow area at the beginning and the end of the strait. These virtual areas will be virtual extensions of the strait, as illustrated in Figure 11.

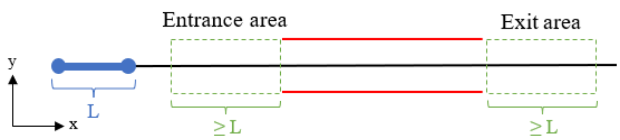

Figure 11: Entering and leaving straits.

On the one hand, studying the entering to the strait, when the robot's front pivot enters the first virtual area previously mentioned (denoted by "Entrance area" in Figure 11), the robot will understand that the strait is near. Then, it will behave as if it was already inside of the strait: the robot will perform the corresponding movements for placing its pivots on each virtual wall (as in Figure 10), and afterwards, it will move forward using the gait of Figure 9, even if it is still in the virtual part of the strait. In this way, it is guaranteed that the robot will not try to approach the strait's entrance by performing wide rotations of 180º, which may produce the collision with the walls of the strait before entering it.

On the other hand, for leaving the strait, a similar procedure is followed. This time the robot understands that this narrow path is finished when its rear pivot leaves the second virtual area (denoted by "Exit area" in Figure 11).

It is important to comment that, in order to avoid any type of collision, the length of both the entrance virtual area and the exit one should be equal or greater than the robot's length L.

Finally, once the robot is completely out, it performs the sequence of movements shown in Figure 6 for returning to be completely aligned with its current straight line.

4. Experiments

This section presents a couple of simulation experiments to illustrate the problems and solutions analyzed in the previous section.

4.1. Comparison of Gaits

In Section 3, we argued that the most efficient gait for the MASAR robot would be by performing 180º turns, since this gait maximizes the traversed distance in a single step. Here, we analyze this by studying the overall time required by this robot to complete a straight-line trajectory 100 times longer than the robot. As Figure 12a illustrates, we assume that the robot starts at the beginning of this trajectory and orthogonal to it. First, it rotates $\alpha/2$ about one pivot, and then it starts to rotate $-\alpha$ or $+\alpha$ about alternating pivots, until reaching the end of the trajectory. We compute the overall time τ necessary for completing this straight trajectory, which is:

$$\tau = T \cdot M(\alpha) + \frac{\alpha}{2\,\omega} + \sum_{i=1}^{N(\alpha)} \frac{\alpha}{\omega} = T\,M(\alpha) + \alpha\left(N(\alpha) + \frac{1}{2}\right) \quad (7)$$

where a constant angular velocity ω is assumed (we set $\omega =$ 1 rad/s for simplicity). $M(\alpha)$ is the number of attachments *and* detachments of the adhesion pads during the whole trajectory, whereas $N(\alpha)$ is the number of rotations of $(+\alpha)$ *and* $(-\alpha)$ necessary for completing the trajectory (note that both M and N depend on α). T is the time necessary for attaching or detaching each adhesion pad (i.e., for switching between its ON/OFF adhesion states).

Figure 12b represents the variation of τ with α, for different values of T. According to this figure, the minimum time occurs for α between 50º and 150º approximately for small values of T, i.e., when using fast adhesion mechanisms that have small attachment/detachment times (the minimum value of τ for each T is represented in Figure 12b as a black dot). However, for sufficiently large values of T ($T > 7$ s approximately), i.e. for adhesion devices that take some time to switch between their ON/OFF states (e.g., for switchable permanent magnets, Peidró et al. 2019) the minimum time is always obtained for $\alpha = 180º$. Note that even for small T, the time τ obtained when using $\alpha = 180º$ is almost the same as the value obtained when using the optimal value for α. Therefore, $\alpha = 180º$ is always a good choice, as intuition suggests.

4.2. Example Path

The combination of movements described in Section 3.3 has been applied to an example trajectory, composed of segments of different lengths and orientations, with narrow straits, as shown in Figure 13a. Figure 13b shows the different poses that the robot has traversed when following this polygonal trajectory, including every 180º turn performed, every change of direction, and every crossing of straits, using the algorithms explained in detail in the previous sections (the robot is represented as a red segment in Figure 13).

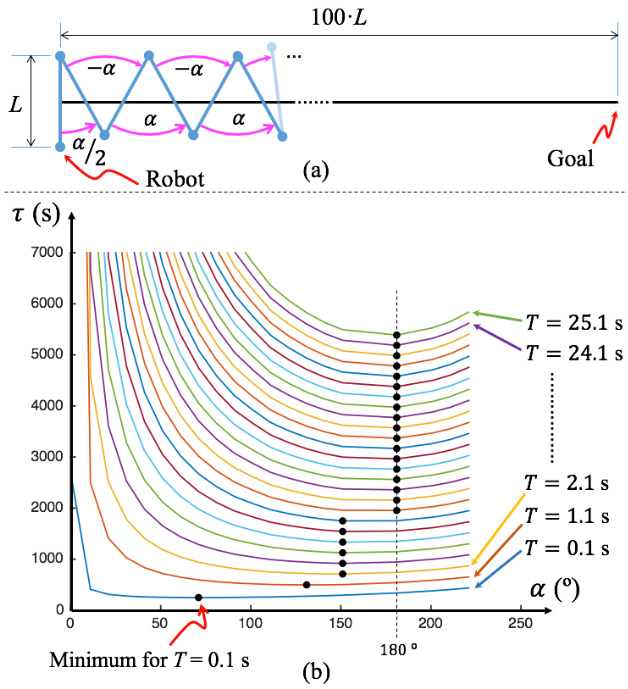

Figure 12: Comparing overall time for different gaits α.

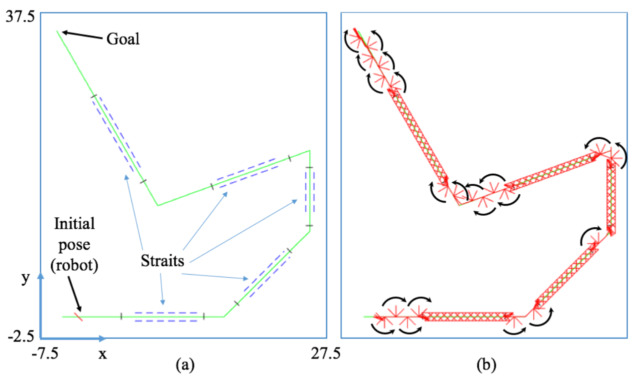

Figure 13: Example of polygonal trajectory with straits.

5. Conclusions and Future Work

In this communication, we have described the MASAR robot: a new Modular And Single-Actuator Robot. This robot is a type-II SAMR since it has binary adhesion pads that can be adhered or detached from the environment in order to produce the rotation of the robot about different axes, achieving in this way two- or three-dimensional motion using only one continuous actuator. In this paper, we have geometrically solved the planar trajectory planning of this robot when following polygonal trajectories that may have narrow corridors that constrain the amplitude of the rotations of the robot. The proposed gait consists in performing 180º rotations when there is no risk of collision between the robot and obstacles of the environment, in order to maximize the distance traveled in a single step. When in straits, the optimal gait consists in rotating the robot until both pivots touch the walls of the strait, since this also maximizes the distance traveled in a single step, subject to the narrowness of the path.

In the future, we will formulate the path planning problem in more general terms, with a merit function to be minimized between endpoints of not-necessarily polygonal trajectories subject to arbitrary-shape obstacles. Also, in the future we will consider the trajectory planning problem in three-dimensional indoor environments made up of concave intersections between orthogonal planes, so that the robot has to make transitions between them and climb as illustrated in Figure 4. The construction and testing of a prototype of the MASAR robot is currently under development. Finally, in the future we will also explore the modular and reconfigurable capabilities of this robot, i.e., we will study the combination of several MASAR modules as illustrated in Figure 5, which can form modular multi-degree-of-freedom articulated robots that can execute more complex tasks than a single module can do.

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