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Strip-Driven Devices for the Spatial Motion Guidance of Human Joints

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***Abstract*— Orthoses and exoskeletons need devices that can replicate the natural spatial motion of human joints. These devices should be simple and should have a high accuracy, in order not to constrain and load the joints unnaturally. In this study, strip-driven devices are proposed to guide the spatial joint motion. Classic planar devices are generalized to obtain rolling without slipping between two ruled surfaces. The special case of spherical motion is presented and analysed in details. The influence of several design parameters on the kinematic and static behaviour of these devices is also presented.**

I. INTRODUCTION

Orthoses and exoskeletons are devices that are generally installed in parallel to human joints to assist the joint motion, or to cooperate with the patient articular structures to provide the correct motion guidance. Thus, it is very important that these devices replicate the joint natural motion accurately, not to oppose further constraints to the joint that could load the articular structures unnaturally. At the same time, these devices have to be light, simple and compact not to hamper the patient.

These two characteristics (accuracy and simplicity) are often opposed, since complex devices are generally needed to accurately guide the joint natural motion [1]. Similarly, very simplified devices are used to reduce the weight and the overall device complexity [2], [3]: this is achieved by adding strong approximations that reduce the accuracy of motion guidance. For instance, many orthosis or exoskeleton joints are planar kinematic pairs, even if the natural joint motion is actually spatial: imposing a planar motion to the joint generates additional constraints that stress the patient articular structures.

In this paper, a family of spatial devices is presented for the guidance of human joint spatial motion. Classic solutions are generalized, to obtain rolling without slipping between two generic ruled surfaces. The particular case of spatial spherical motion has a particular relevance in this field and generates simple solutions that are analysed in details. The proposed devices are versatile, simple and compact, and have virtually no slipping. All these features are particularly important for the orthosis and exoskeleton design [4], [5].

II. DEVICE DESCRIPTION

A. Classic planar solutions

The devices proposed in this study can be obtained as a generalization of previous devices that have been used to generate a planar relative motion between two rigid bodies through flexible strips. The most common examples are the cross-strip rolling pivot [6] and the Rolamite [7] devices. The cross-strip rolling pivot devices represent a family of planar kinematic pairs that allow rolling without slipping between two given general shape cylinders. Fig. 1 shows an example of these devices: two cylinders C_a and C_b with circular section are connected by two crossed flexible strips s_1 and s_2 in a different axial position. An end of s_1 is rigidly attached to C_a, the other end to C_b; the ends of s_2 are attached to C_a and C_b in a similar but reversed way, so that the two strips in a view directed as the axis of the cylinders cross at a point P; the length of each strip is adjusted so that the two cylinders remain in contact at the point P. This device allows pure rolling between C_a and C_b on the crossing point P; as a consequence, P is the pivot point (or the instantaneous rotation centre) of the planar relative motion between C_a and C_b.

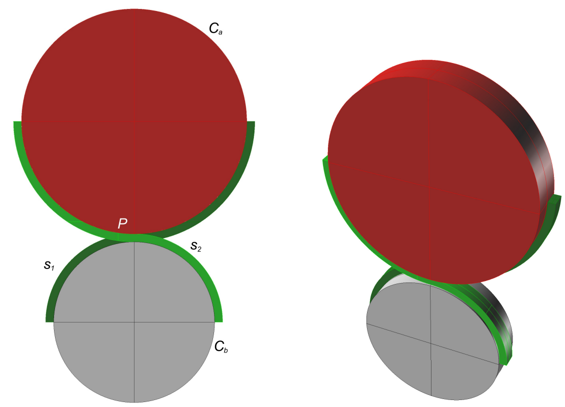

Fig. 1. The cross-strip rolling pivot device.

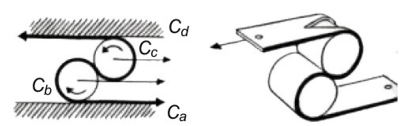

Fig. 2. The Rolamite device. (©Popular Science)

The two considered cylinders have circular sections. The same result can be obtained also by using general section shapes, provided both C_a and C_b have convex sections (at least on the contact arc) in order to maintain the strips in contact with the surfaces. For instance, a limit case that has a practical interest can be obtained by choosing a plane surface for C_a and a general convex surface for C_b. The Rolamite device cited in the previous paragraph is a variation

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of this particular case, that guarantees a higher stiffness and provides a solution that needs just a single strip (Fig. 2). The strip is attached at one end on a plane C_a; the strip then wraps two cylinders C_b and C_c in opposite directions and its second end is attached to a second plane C_d, parallel to the first one. Each cylinder can roll without slipping on the other cylinder and on the relevant plane, allowing translation of the group composed by C_b and C_c.

B. New spatial solutions

The devices described in the previous section are planar and thus they make it possible to generate a planar relative motion between two rigid bodies. These devices could be used as kinematic pairs for orthoses and exoskeletons to guide the joint motion. Indeed, they are extremely versatile since, apart from the limitation of surface convexity, virtually all cylinders with any planar directrix can be used, thus allowing even complex relative motions to be generated. Moreover, they are simple and compact: they have the same advantages of compliant mechanisms in this sense, and can be built by a few components. Finally, these devices allow a relative motion virtually without slipping.

However, as pointed out in the Introduction, the main problem is that the motion of many human joints is spatial and can be represented as a planar motion just through strong approximations. For instance, the femur and tibia relative motion of the knee was modelled in several lower limb models and medical devices by a hinge joint [3], [8] or by other planar mechanisms, like the four-bar linkage [2], [9]. These mechanisms cannot replicate the out-of plane motion components (like the in-external tibia rotation) that require more complex spatial models [1]. As a consequence, planar orthosis or exoskeleton joints unnaturally constrain and load the natural joints, and could generate pain or other problems to the patient. Thus, planar devices like those described in the previous section could not be an optimal solution to guide the motion of all those joints whose motion is not planar.

To overcome these limitations, new spatial devices are proposed in this study that can generate a spatial relative motion between two rigid bodies by means of flexible strips. In particular, these devices allow rolling without slipping between two spatial ruled surfaces with general shapes. These surfaces are in contact instantaneously at a line r that lay completely on both surfaces. There are just two limitations on the surface shape, that will be clarified in the following:

1) The surfaces must be convex or there must exist at least three sections that are convex in the contact arc and that intersect all contact lines r;
2) The translation along the contact line r must be instantaneously null or extremely low.

A particular motion that satisfies the second requirement and that has a practical interest is the spherical motion. The relative motion of two rigid bodies is spherical if it exists a point in space where the relative displacements between the two bodies are always null. Two ruled surfaces generate a spherical motion if they are generalized cones with common vertex; the common vertex is the centre of the spherical motion.

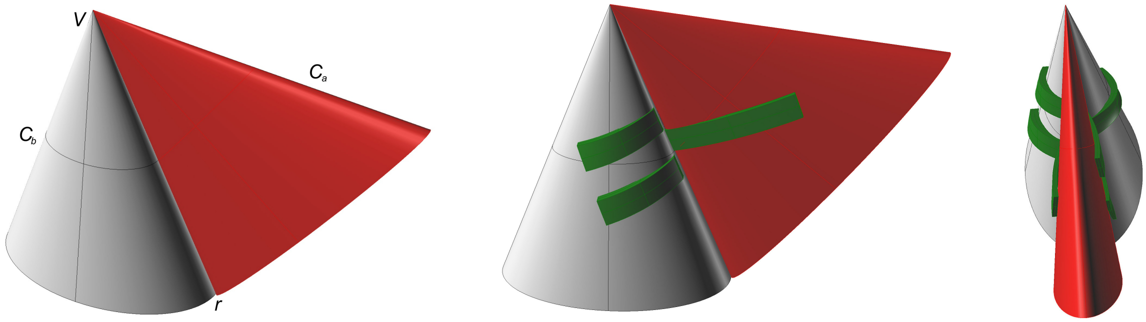
Only spherical motion is considered in this study, since it is sufficiently general, it has a practical relevance and it allows a simple visualization of the ruled conical surfaces. As for the generality, all generalized cones can be considered, provided their curvilinear directrix satisfies the first requirement: both directrices must be convex curves, at least in the contact arc. As for the practical relevance, some studies prove that several human joints have an almost spherical motion [10]–[13]: the proposed devices can be used to guide the spatial motion of these joints with a good accuracy. As for the visualization, generalized cones can be easily represented and developed on a plane.

Two representative cones C_a and C_b are shown in Fig. 3(a); these cones are used as an example to describe the proposed devices. Elliptical directrices have been chosen in this case, but (as already reported above) more complex directrices could be considered. The two cones are in contact along a common line r and have the vertex V in common: if the two conical surfaces roll without slipping one on the other, the generated motion is a spherical motion.

Flexible strips are used to generate the rolling without slipping motion, like in the planar case (Fig. 3(b)). As a first example, linear axis rectangular strips are considered, but different strip shapes could be considered to optimize the axial dimensions of the device. This aspect is discussed in section III-B. Each strip is connected to the cones in a very similar way as the planar case: one end is connected to the cone C_a, while the other end to C_b; the length of the strip is adjusted so that the two cones remain in contact at line r. Thus, each strip partially wraps C_a from the first end to the contact line r; then, it partially wraps C_b from the contact line r to the second end (Fig. 3(b)). All strips are connected in a similar but alternately reversed (crossed) way to the considered cones. The main difference with respect to the planar case is that at least three strips are required in the spatial case: this is a requirement to constrain rotations in both clockwise and counter-clockwise directions about the perpendiculars to r that are instantaneously in common to both conical surfaces. This is also the reason for the first restriction on the ruled surface shape: the three strips have to lay on convex curves, in order to maintain the contact with the surfaces. As for the second restriction, instead, just very small translations (due to clearance or strip stiffness) are allowed by the device along the contact line r.

C. Spherical motion generation

These spatial devices allow pure rolling without slipping of the two conical surfaces on the contact line r; as a consequence, r is the instantaneous rotation axis (IRA) of the relative motion between C_a and C_b. The behaviour of the strips during motion can be easily represented by developing the cones on a flat surface. The two cones in Fig. 3(a) are developed on a plane in Fig. 4, together with one strip (the other strips are not represented, for the sake of clarity). In particular, Fig. 4(a) represents the two developed cones C_a



(a) Two representative cones.

(b) Flexible strips.

Fig. 3. The spatial cross-strip rolling device: the two representative cones (a) and the flexible connecting strips (b).

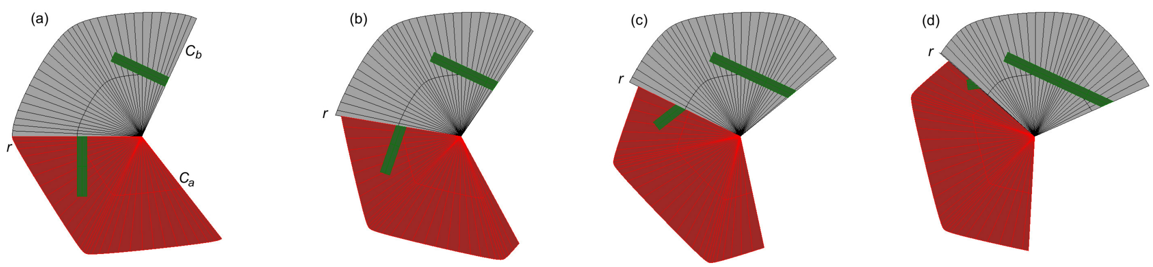


Fig. 4. The rolling of the two cones, represented on a plane at four different positions.

and C_b at the same position of Fig. 3(a), with the same colour and with the same dimensions: the cones are instantaneously in contact at the horizontal line r between the two developed surfaces; as an example, the dimensions of the cones are chosen in a way that the contact line length at the starting position is the same for both the cones (Fig. 3(a)– 4(a)). The green flexible strip is rectangular (as already reported above): it wraps the red cone (C_a) from the first end to r; then it wraps the grey cone (C_b) from r to the second end. Since the strip wraps C_b in the opposite direction with respect to C_a, the strip appears in the opposite side of the developed surface.

The direction of the strip with respect to the two surfaces is arbitrary: the angle of the strip axis with respect to r at the starting position (90 degrees in Fig. 4) can be arbitrarily modified. Whatever direction is chosen, the distance of the strip from the cone vertex is not constant if the strip is rectangular. In other words, the strip cannot lay on a section perpendicular to the cone axis in this case.

Fig. 4(b) represents the two developed cones C_a and C_b at a subsequent step: C_b is fixed, while C_a rolls over it. In particular, the contact line r moves in clockwise direction, together with the red surface that rotates in clockwise direction. The two cone sectors that entered in contact during the rolling from Fig. 4(a) to Fig. 4(b) are now in the opposite sides of the developed cone surfaces. In particular, the strip length on C_a is reduced, while it is increased on C_b, since the strip unwraps C_a and, at the same time, wraps C_b during rolling. Fig. 4(c)–(d) show the same motion at subsequent steps. It can be noticed, in particular, that the contact line length varies and, at different steps, the length on C_a is different from the length on C_b. Moreover, the angle of the strip axis with respect to r changes: the section length of the strip on r changes, an aspect that should be considered to avoid interferences between strips (when the other strips are connected to the device) or to evaluate the device stiffness.

III. Device optimization

A real design of the proposed guiding devices depends from the particular application and thus it is not presented here: structural and functional details should be defined to best-fit the application scopes and requirements. As for structural details, in general any string and connecting element could be used, providing their stiffness is sufficiently high for the particular application. As for the functional details, several aspects have to be considered to optimize the proposed guiding devices, apart from the cone shapes. The effects of cone truncation, strip shapes and IRA position and orientation should be analysed, since they influence the device dimensions and its kinematic and static behaviour.

A. Cone truncation

Cone truncation is always a need to reduce the axial dimensions of the device. From a kinematic point of view, the truncated cone must contain all strips at all rolling positions. If the number of strips and their dimensions are given, the minimum axial dimensions of the device depends from several parameters. The strip shape has a strong influence that will be clarified in the subsequent section. The range of motion and the cone shapes affect the strip length and the way the strips wrap the cones. Moreover, the change to the contact line length during motion (Fig. 4) should be considered also, in particular if, for several reasons, one of

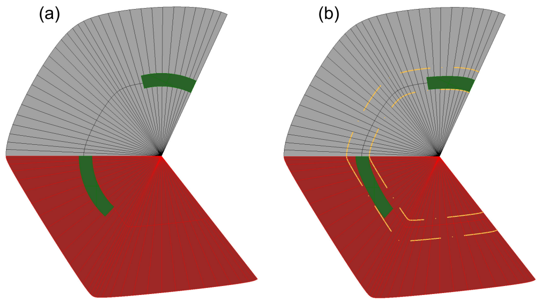


Fig. 5. Strips with different shapes: (a) circular shape, (b) C_b directrix shape.

the two surfaces must remain in contact with the other one on all its width.

In this sense, cone truncation can be performed in different ways. A planar truncation (perpendicular or not to the cone axis) is the simplest solution, but other shapes could reduce the axial dimensions of the pair, in particular if a simple strip shape (i.e. rectangular) is considered.

B. Strip shapes

Strips are considered rectangular in the previous examples, but strip shapes could be also different. Two further examples are presented in Fig. 5, where a strip with a circular shape and one with C_b directrix shape are represented. These solutions better approximate the cone directrices. In particular, the example in Fig. 5(b) works well in this case, but it could not be the best solution in general: the strip shape is the C_b directrix, that does not necessarily approximate the C_a directrix as well. This aspect could generate problems during strip wrapping.

Basically, there could be two reasons to make strip shape similar to the cone directrices:

1) The strip remains almost perpendicular to the contact line during the full arc of motion. This aspect reduces the risk of strip interferences and, depending on the application, it could improve force transmission.
2) If the cones have to be truncated by a plane perpendicular to the cone axis, this solution guarantees low axial dimensions of the device.

As for the second point, Fig. 5(b) shows the maximum truncation of the cones (dashed orange curves), by means of planes perpendicular to the cone axis; the contact line length is the same for both surfaces at the starting position, for consistency with the previous figures. The width of the cones is actually small.

Advantages or disadvantages concerning other strip shapes depend on the particular application. In general, as pointed out in section II-C, the position and orientation of each strip on the cone surfaces are not fixed and could also be considered further parameters to optimize. Moreover, the choice of the best strip shape should be performed after a careful analysis of the forces: the strip shape influences the device stiffness; in particular, it affects the resistance opposed by strips to rotations about the common perpendiculars to r.

C. IRA position and orientation

The real position and orientation of the IRA should be considered during the optimal definition of these guiding devices. This axis has been thought coinciding with the contact line r (Fig. 3(a)), that is an ideal case, but the real situation could be different.

Firstly, the loads applied to the device could separate the two surfaces, due to the device stiffness. The device can work even in these conditions, but the exact position and orientation of the IRA depends from the loads. Strip thickness is a second cause: actually, the contact between the two rolling surfaces is mediated by the strips and thus the real IRA lies between the two surfaces C_a and C_b (depending on the strip strains) in the space taken up by the strip thickness. Direct contact between the cones could be restored by grooves that hold the strips.

IV. Conclusions

Strip-driven devices are proposed for the guidance of the spatial motion between two rigid bodies. These devices make it possible to obtain rolling without slipping between two given ruled surfaces. The particular case of spherical motion guidance is described and analysed in details. The advantages of the proposed solutions, such as versatility, no slipping, simplicity, few components and compactness, make the proposed devices particularly useful in orthosis and exoskeleton design.

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