Enhanced experience and safety in Interactive Robotics

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Summary

Interactive Robots work directly in contact with human beings; hence safety is a critical issue. Their design is usually a trade-off between safety and performances. They should not oppose any resistance when moved by hand in open space (backdrivability) – which requires low inertia, low friction, characteristics which belong to small actuators, and they should be able to create high transient forces in order to be as responsive as possible, which requires potentially dangerous high torque motor.

In order to overcome this contradiction, a self-locking motorized articulation has been introduced. It allows for unilateral stop of the motion without extra or over actuation in such a way that inertia and back drivability are not compromised. A further enhancement adds self-tuning for robustness against dimensional uncertainty and weariness.

The paper describes the solutions and the solving process.

Keywords: Interactive robots, Haptic Interface, Cobot, safety, TRIZ, ARIZ, OTSM-TRIZ

1. INTRODUCTION

Interactive Robots are force feedback device that have physical contact and force exchange with humans. They translate the position of the hand of the operator into a desired position for the system executing the task and in return translate the interacting forces, whether real or computed, between the environment and the controlled tool towards the hand of the operator. The main challenge they are facing is that they should not disturb the operator while moving freely in open space. It requires very low friction and very low inertia, which can only be done with very small actuators or even no actuators. But they should also be able to provide high transient forces for instance to emulate a contact with a very stiff environment such as a wall. This requires high torque and stiffness, which in turn needs larger actuators.

Cobots (acronym for Collaborative robot) are both control and executing devices. They share the task and manipulate the tools together with the operator. They also should be backdrivable and be able to deliver the forces required by the task. For them safety is an even more critical issue since the operator and the task can be harmed. Cobots are used for two different reasons. The most popular is to enhance the operator force in order to alleviate the heaviest task and thus prevent tiredness and muscular troubles.

Figure 1. A cobot for hard task (credit RB3D)

We can see in Figure 1 a cobot which provides an amplification of the operator force.

But there are other applications where force augmentation is not necessary but improved accuracy, precision and safety. Let's consider the case of orthopedic surgery and more precisely spinal surgery which threaten to become a national healthcare issue.

2. Initial situation

2.1. Problem description

The growing number of old people who will need spinal surgery combined with the forecast lack of skilled surgeons may become a critical healthcare problem. Better training suffers from the lack of cadavers. A multi-modal virtual learning platform has been proposed [1]. But yet there is no satisfactory rendering of blood and other biological liquid which invades the surgical area. An assisting device for bone surgery was introduced in order to both reduce time of operation and enhance safety while cutting and grinding bones in the close vicinity of the spinal cord [2]. Figure 2 shows an associated graph of problems [3].

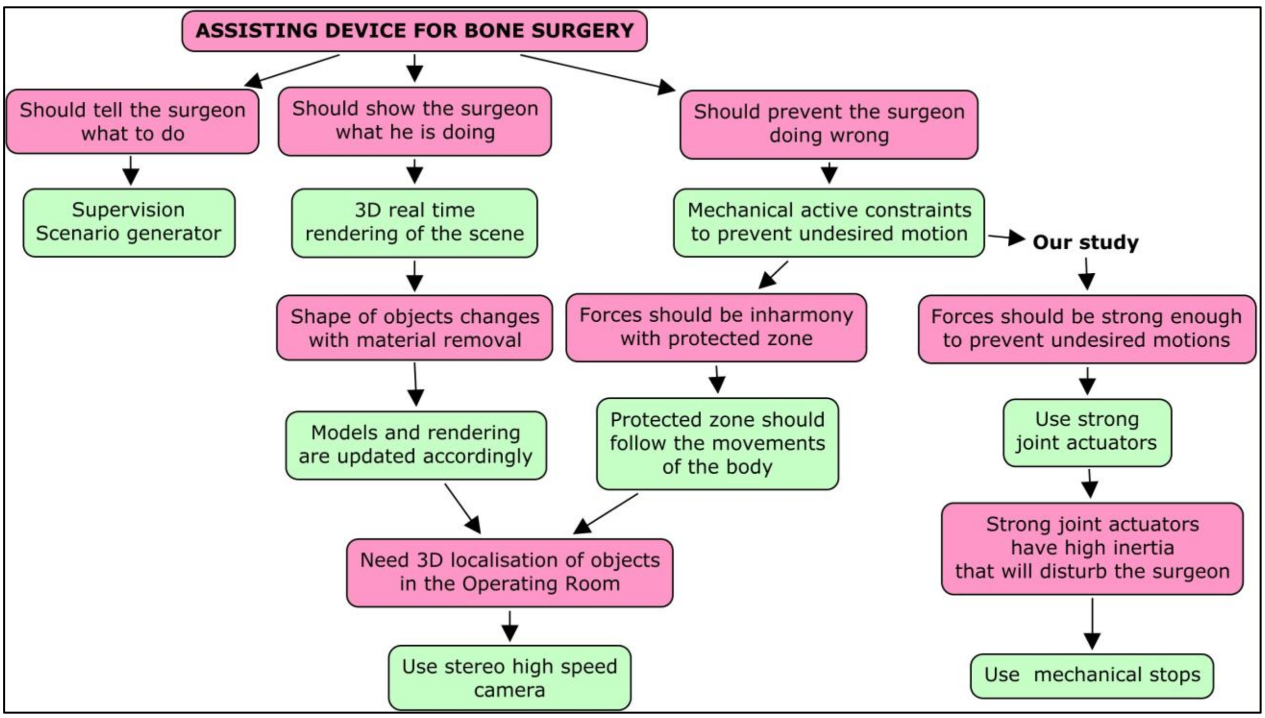

Figure 2. Graph of problems for an assisting device in spinal surgery

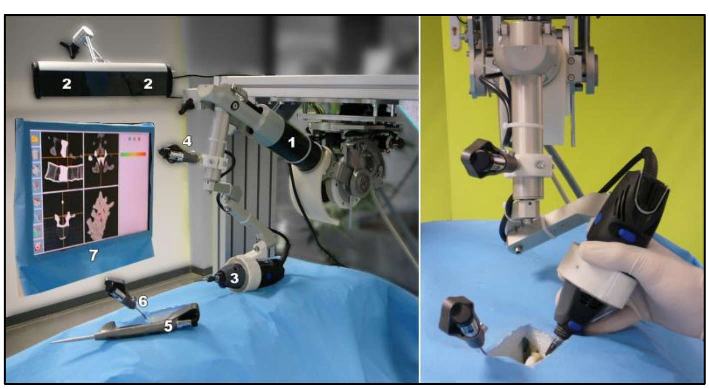

Figure 3. Surgicobot: a cobot for spinal surgery

Figure 3 shows a cobotic system which provides a complete environment for spinal surgery, including supervision of the task, navigation of the tool and 3D real time representation of the grinding operation. The active tool is manipulated by both the surgeon and the cobot who share the task. The decision remains with the surgeon while the cobot will provide assistance. The main function of the system is to create a protective shield around critical organs with high repelling forces to prevent any intrusion. Everywhere else the cobot should not disturb the surgeon who wants to keep his manual comfort.

Some of the subsystems are already performing well and are still continuously improving (speed and precision of the camera, accuracy of the geometric models and speed of its update, ergonomic of the interface). Nevertheless the actuating subsystem which happens to be the most influential has had little improvement. This probably happened because it faces a major contradiction. The actuators should be light enough not to disturb the surgeon while he is working far from critical organs, and should be strong and stiff enough to prevent unwanted penetration in the protected area. At this point it should be made clear that the use of a brake is not convenient because it stops the motion in both directions, preventing the surgeon to move backward without releasing the brake. A discussion on different actuating concepts can be found in [4]. The protection means the ability to stop the moving parts. First the joint motor is used until the required torque exceeds its capacity.

An additional device should be used to help the motor.

2.2. Concept of solution

A simple concept of solution, able to stop the moving part in a single direction is depicted in Figure 4.

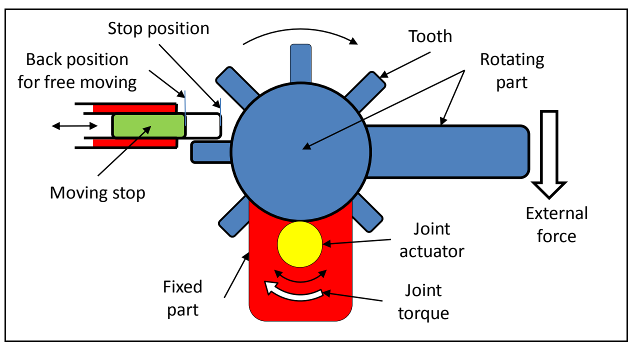

Figure 4. Moving part with teeth

There is a rotating part with teeth. There is a stop with two positions, being inserted between two teeth to stop the motion of the rotating part in a single direction. The stop is moved by a motor.

If there are few teeth then they are strong enough to stop the moving part but there are few stop locations.

If there are many teeth then they are not strong enough to stop the moving part but there are many stop locations.

This new problem is solved with ARIZ and OTSM-TRIZ [5][6][7][8].

3. SOLVING PROCESS – FIRST SOLUTION

3.1. ARIZ step 1

The Technical System for stopping a rotating part in a single direction, at the right place includes a fixed part, a rotating part with teeth moved by a small joint actuator, a stop moved by a motor and external force applied on the rotating part.

The Physical Contradiction can be written this way:

PC1 - If there are few teeth then the motor does not need to be powerful but there are few stop locations.

PC2 - If there are many teeth then there are many stop locations but the motor needs to be powerful.

It is necessary, with minimum change to the system, to get many stop locations and a small motor.

The system should be stopped everywhere so PC2 is chosen.

The **Tool** is the moving stop and the **Product** is the moving part. In this case the product can be modified.

Intensified formulation

There is an infinity of teeth. The moving part can be stopped everywhere but the teeth are too weak.

One must find an X-Element that eliminates the weakness of the teeth and can stop the rotating part in a single direction everywhere.

Comment1: an infinite number of teeth on a given circumference means the teeth become so tiny that the surface becomes circular and slick. The problem seems to become harder.

Comment2: for simplicity reason we decided to discard the use of any motor (and associated electronics and control) to move the stop!!

The problem can be reformulated as:

There is a moving part with a slick circular contact area. There is a mechanical stop but no motor.

One must find an X-element that can stop the slick circular rotating part in a single direction everywhere without motor.

3.2. ARIZ step 2

The Operating Time: Moment when a stop is needed and the external force exceeds the joint motor torque.

The Operating Zone: The contact zone between the stop and the rotating part.

SFR Analysis

Moving part	- substance
Stops	- substance
Fixed part	- substance
System	- field: joint motor torque, external force , thermal field, electromagnetic field.

3.3. ARIZ step 3

IFR1

The X-element, without complication of the system and without harmful side effects,
eliminates < the non stop of the moving part caused by the absent teeth and absent stop motor >
when < a stop is needed and the external force exceeds the joint motor torque >
at the <Contact area between the moving part and the stop>,
and keeps the ability to stop the moving part everywhere.

Use only the SFR

Mechanical stop (Tool). The Mechanical stop should stop the moving part in a single direction at OT, in OZ.

Parameter: friction coefficient. Even high friction coefficient would require high pressuring force. Furthermore the stop would act in both directions which is prohibited. That is why teeth were used. If the stop is sharp and hard it could create a temporary tooth in the moving part. This indentation should disappear when the contact with the stop is lost. But it is not easy to get a unidirectional stop.

Moving part (Product). The moving part should stop the moving part in a single direction at OT, in OZ.

Parameter: shape. The moving part belongs to our system so it could be changed accordingly to change of shape of other components which would keep control of the modification.

Fixed part. The fixed part should stop the moving part in a single direction at OT, in OZ.

Parameter: shape. The shape changes and something grows towards the moving part. The effect on the moving part could be friction, but friction is insufficient to stop the moving part. The effect could be indentation in order to create a perpendicular face able to stop the motion.

Parameter: number of components (fractioning). A part of the fixed part can be made mobile in order to produce friction or indentation. This part should come from a simple modification of the fixed part. It may seem odd and going backwards.

Joint torque motor. The joint torque motor should stop the moving part in a single direction at OT, in OZ.

Parameter: magnitude. We know from the beginning that this does not work. This is the root cause of the problem. But what can be done is to block the transmission of the motion between the motor and the moving part, like a grain of sand in the gear. The physical effect is butting, which totally prevents motion in one direction as soon as the angle between the contact reaction forces is inferior to the Coulomb friction angle. This is exactly what we need!!! We keep it.

External force. The external force should stop the moving part in a single direction at OT, in OZ.

Parameter: magnitude. When the force exceeds the joint motor torque, then the moving part moves. Butting comes from reaction forces. There are reaction forces in the motor attachment and in the pivot of the moving part that can be used.

We overlooked Electromagnetic field, although being highly controllable for the same reason we discarded the motor. We also eliminated Thermal Field, although it can create very high forces, for being too slow, especially when cooling is required.

IFR2

There is a fixed part with a motor driving a rotating moving part submitted to external force. There are reaction forces. When the external force exceeds the motor force then a contact point should move in order to align the reaction forces accordingly to the butting condition.

The pivot of the moving part should not be changed since it dictates the output position of the cobot.

But the motor attachment could move a little in order to create butting with the moving part.

3.4. Result and comments

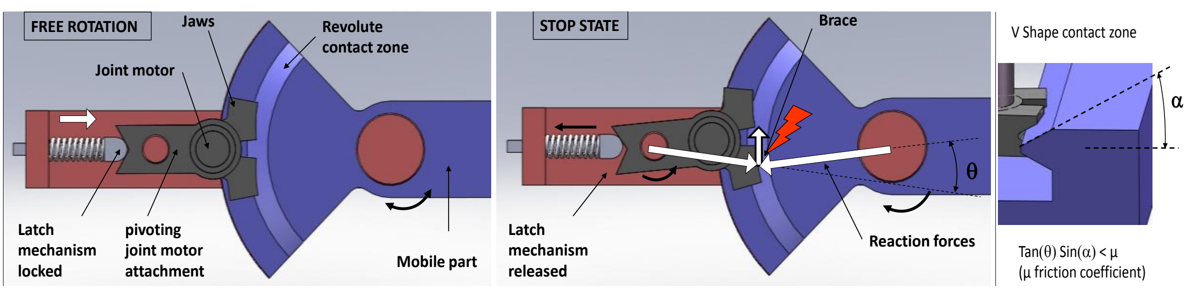

Figure 5. A self-locking cobotic joint

Figure 5 shows a solution with a rotating joint motor attachment holding jaws that are put in contact with a V-shape contact zone of the moving part (a conical disc). The angular alignment of the contact forces follows the butting condition with μ the friction coefficient of the Coulomb model (1).

$$Tan(\theta)\ Sin(a) < \mu \qquad (1)$$

A simple latch mechanism holds the motor attachment. The latch force is tuned just below the maximum motor torque. For inferior torque motor value, the stopping system has no effect [9] [10].

Unfortunately we never were able to make it work properly, despite careful tuning. In fact the system requires that the jaws and the brake disc are perfectly fit when they get into contact, whatever the angular position and the rotating direction. In fact, the smallest error, whether angular or axial, results in a gap impossible to close between the disc and the jaws. No pressure is applied on the disc and the stop does not occur. Something else should be done.

4. SOLVING PROCESS – SECOND SOLUTION

The system comprising conical jaws and a conical disc was submitted to the Evolution Laws. Manufacturing and assembly constraints of the disc show that few changes can be made. So we decided to keep the disc as is and to focus only on the jaws. The jaws should compensate for axial position error, angular position error and geometrical error of the disc (radius, conical angle). The current one piece design is an obstacle.

The Law of Harmonization says that the correction should be effective at the moment when the jaws and the disc are put in contact. Further on we can state that the contact force should perform this correction. But how?

With the Law of Dynamization a first idea comes to mind. An axial displacement of the jaws can be allowed. The left and right sides of the jaw can be made independent and each one can translate axially inside a guide. The conjugate form of the disc and the jaw will push the jaw at the right position when touching the disc. Obviously the guide should prevent any tangential displacement of the jaws to ensure the clamping of the disc.

This idea is applied to the angular corrections. The jaws should be allowed small angular displacements around two orthogonal axes lying in the symmetry plane of the disc. A new contradiction appears about the size of the bearings which should be large enough to stand the forces and small enough for an easy integration. This proved not possible.

Going further with Dynamization leads to imagine a flexible part which could flex around the two aforementioned axes and keeps on preventing tangential motion. Some example of such a solution is given in Figure 6.

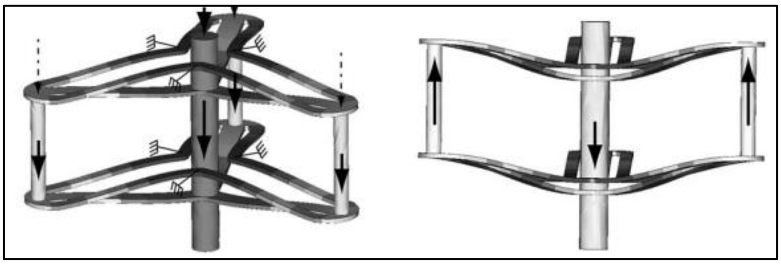

Figure 6. Example of flexible support of the jaw. Discarded solution

But enough angular motion can only be obtained at the expense of dimensions and integration would a new issue..

Deeper investigations show that the jaws themselves should be dynamized to compensate for geometrical difference with the disc. A very small error on the conic angle would prevent any correct contact.

The system is reduced to a jaw with superior and inferior side, a conical disc and radial motion of the jaws towards the disc. And the contact with the disc can occur at different angle. What can ensure that this contact will occur properly whatever the relative orientation of the surface at the contact point? One SFR was left aside yet, the shape of the jaw. Only a sphere has tangential surfaces oriented in all directions. So the surface of the jaw should be spherical.

Figure 7, Figure 8 and Figure 9 show that such a device can compensate for all geometrical uncertainties, inclusive changing uncertainties caused by weariness.

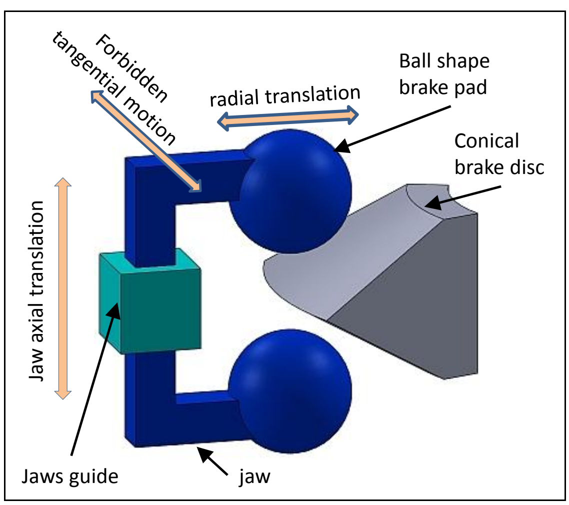

Figure 7. Concept of self-compensating brake pad

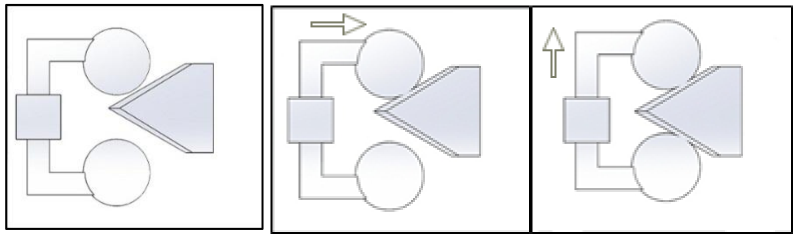

Figure 8. Axial error compensation

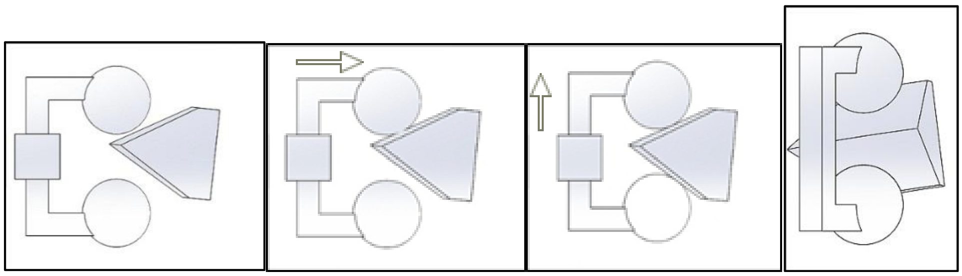

Figure 9. Two axes angular error compensation

A small radius of curvature of the brake pad would compensate severe angular error, but the small contact print will create high stress. In fact the radius should be chosen in harmony with the value of the assembly and manufacturing angular error that can occur in the system. The pad does not need to be a perfect ball, only the face in contact with the disc has to be curved as shown in Figure 10. Furthermore the radiuses of curvature in both directions are not necessarily equals.

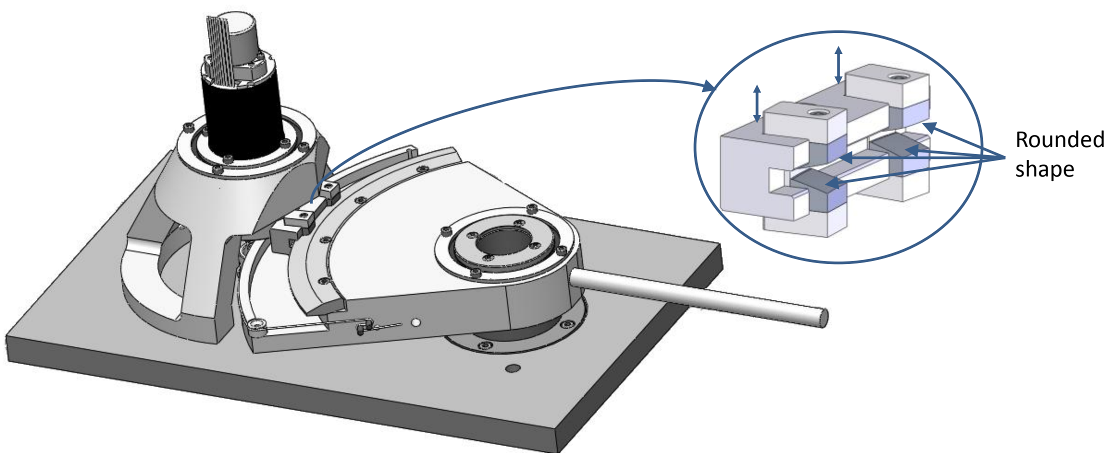

Figure 10. Mockup of self-locking robotic joint with self-compensation butting jaws

5. Results

The tests with this prototype were immediately successful. The system is easy to tune for different values of locking torque. The safety of cobots can be greatly enhanced. This novel device can be also considered for exo-skeletons to alleviate the motors in some static positions where the required torque is high, in order to reduce energy needs. It can be used to get a better experience with haptic devices which yet struggle to emulate contact with stiff environments like walls.

6. CONCLUSION

Two successive solving processes were conducted as unforeseen problems arouse with the first prototype. The first step, which should result in a technological breakthrough, was mainly solved with ARIZ. In the second step the solutions came quite in a continuous flow with the Laws of Evolution.

Once more, TRIZ proved its efficiency [11] [12].

REFERENCES

[1] Gosselin, F. et al.: Design of a Multimodal VR Platform for the Training of Surgery Skills. EuroHaptics 2010, Amsterdam, July 8-10, 2010.

[2] Riwan, A. et al.: Surgicobot project: Robotic assistant for spine surgery. In: IRBM 32 (2011) 130–134

[3] Cavallucci, D., Rousselot, F., Zanni, C.: Initial situation analysis through problem graph. (2010) CIRP Journal of Manufacturing Science and Technology, 2 (4), pp. 310-317

[4] Van Rhijn, J.; Riwan, A.; Jabbour, Z.; Arakelyan, V.: Mechanical impedance: a cobotic and haptic actuators performance criterion. EuroHaptics 2010, Amsterdam, July 8-10, 2010.

[5] Van Rhijn, J.: Contribution à l'étude et au développement des systèmes adaptables pour les robots reconfigurables : Application à la cobotique. PhD Thesis, 2011.

[6] Altshuller, G.: Creativity as an Exact Science. Gordon and Breach, Science Publishers, Inc., 1984.

[7] Altshuller, G.: ARIZ in "Rules of a Game Without Rules". 1989, Petrozavodsk: Karelia, ISBN 5-7545-0108-0

[8] Khomenko, N. ; Classical TRIZ and OTSM as an applied scientific theories, Frankfurt am Main, Germany.

[9] Khomenko, N. ; Yoon H., OTSM express analysis of an initial situation, TFC 2011, Dublin, Ireland

[10] Riwan, A.;Van Rhijn, J.: Motor driven self-locking articulation for a robot arm.: Patent WO 2011/042151

[11] Riwan, A.; Bonnemason, J.; Ponsort, D.: How the use of TRIZ led to design a novel bistable electromagnetic fastening device, TFC2012, Lisboa, Portugal, 2012.

[12] Riwan A.: Triz helps blind people to find their way in subway stations, TFC2013, Paris, France, 2013.

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