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Editors

International Centre for Mechanical Sciences

ROMANSY 18 Robot Design, Dynamics and Control

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INTERNATIONAL CENTRE FOR MECHANICAL SCIENCES

COURSES AND LECTURES - No. 524

ROMANSY 18

ROBOT DESIGN, DYNAMICS AND CONTROL

PROCEEDINGS OF THE EIGHTEENTH
CISM-IFToMM SYMPOSIUM

EDITED BY

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PREFACE

The First CISM-IFToMM Symposium on Theory and Practice of Robots and Manipulators was held on September 5-8, 1973, in Udine, Italy, not long after IFToMM had been founded in 1969. The first ROMANSY, or Ro.Man.Sy., as the Symposium used to be referred to, marks the beginning of a long-lasting partnership between two international institutions, CISM, the Centre International des Sciences Mécaniques and IFToMM, the International Federation for the Promotion of Mechanism and Machine Science.

As the 18th Symposium returned to Udine, Ro.Man.Sy 2010 continued to preserve this tradition, by encouraging papers that are of a broad interest to the participants and by providing an environment and setting for meaningful technical and personal interactions among the delegates. In particular, the conference solicited papers providing a vision of the evolution of the robotics disciplines and indicating new directions in which these disciplines are foreseen to develop. Paper topics include, but are not limited to:

1. *robot design and robot modules/components;*
2. *service, education, medical, space, welfare and rescue robots;*
3. *humanoid robots, bio-robotics, multi-robot, embodied multi-agent systems;*
4. *challenges in control, modeling, kinematical and dynamical analysis of robotic systems;*
5. *innovations in sensor systems for robots and perception;*
6. *recent advances in robotics.*

The 18th ROMANSY took place July 5-8, 2010 in Udine, Italy and was enriched with three keynote lectures presented by Makoto Kaneko from Japan, Jorge Angeles from Canada and Andres Kecskeméthy from Germany, who discussed new trends in applications and methodology. During the conference banquet a ceremony was arranged for the two recipients of the IFToMM Award of Merit 2010, Alberto Rovetta from Italy and Atsuo Takanishi from Japan, with a speech about IFToMM honors and awards, the presentation of each recipient by their nominators, the delivery of IFToMM honors and awards to recipients, and a short speech by each recipient.

The following scientists served on the Steering Committee of Ro.Man.Sy. 2010:

- *P. Bidaud (Laboratoire de Robotique de Paris, France)*
- *M. Ceccarelli (University of Cassino, Italy)*
- *I-Ming Chen (Chair of TC Robotics, Nanyang Technological University, Singapore)*
- *B. Heimann (Leibniz Universität Hannover, Germany)*
- *O. Khatib (Stanford University, USA)*
- *E. Martin (Canadian Space Agency, Canada)*
- *W. Schiehlen (CISM Representative, University of Stuttgart, Germany)*
- *A. Takanishi (Waseda University, Japan)*
- *T. Zielinska (Warsaw University of Technology, Poland)*

The Steering Committee reviewed together with the Symposium Co-Chairmen the 62 submitted papers and accepted 54 contributed papers from 19 countries. In this volume three keynote papers and the contributed papers are published after some revision.

The participants enjoyed the stimulating environment at CISM and the great service of the CISM staff. In particular, Mrs. Paola Agnola did an excellent job starting already in 2007 with the proposal for hosting Ro.Man.Sy. 2010, and continuing with the service for the co-chairmen and all the participants up to the closing of the Symposium. Thanks are also due to the printing office of CISM and Springer-Verlag Vienna for the efficient cooperation in publishing this proceedings volume.

Vincenzo Parenti Castelli, University of Bologna
Werner Schiehlen, University of Stuttgart

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Where Future Robots should Go and should not Go

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Abstract Where future robots should go and should not go and what is an adequate style of collaboration between human and robots? These questions are really interesting for discussing the future direction of robot, especially from the design point of view. While it is really hard to find a general answer for these questions, we try to provide our answers, particularly focusing on manipulation area, by reviewing our former works and exploring a success example of robot business. Our eventual message is that we should cut the function of "manipulation of object within hand" as an end-effector and focus on a hand with single purpose rather than universal hand.

1 Introduction

While many industrial robots are working in factories, robot businesses in other fields except industrial area are not so popular. In research level, a number of robots have been designed and developed in various fields so far all over the world. However, most of them have been fade away or will be so in the future. It is really hard either to send robots to a market or to keep continuously selling robots in market. People are easily tired in playing and enjoying with robots if they are toys or entertainment robots. In order to keep selling or increasing market continuously, there is a necessary condition where the robot is definitely necessary for human or human receives a serious damage without the robot. Of course, there is a category of weaker level, such as "convenient" instead of "definitely necessary". Home robots are categorized into the level of "convenient". As for home robots, people are expecting them to work outside of house as well as inside of house, instead of human. In this case, house wives will make decision whether they should buy or not, by considering the balance between the investment and the acquired convenience. At this point, we have to be careful for the reliability

(a) (b)

Figure 1. Juggling and manipulating a pencil.

of home robot, while this issue is not taken into consideration seriously. Suppose a home robot with the success rate of 99%. This success rate is quite high in research level. Now, suppose that a family with four members is taking meals for breakfast, lunch and dinner, and they utilize three dishes for each meal. As a result, the family utilizes 36 dishes per day. If the home robot with the success rate of 99% is supposed to make clean dishes after each meal, it will break one dish every three days. House wives will never buy such a robot. Even human are dropping a glass perhaps once a year. In order to keep reliability as human do, we have to design a home robot with the success rate of 99.99%, while it seems to be very hard for current robots to keep such a high reliability. We believe that this is a hurdle for home robots to clear.

On the other hand, if a robot is categorized into "definitely necessary", people will buy it, even though the price of robots is so expensive. This case does not happen for home robots but may happen for medical robots where human will either get a serious damage or eventually die without an assistance of such a robot. The robot which is definitely necessary will be never fade away, as X-ray based examination will be never in medical area. At the same time, such a robot includes essential functions while other robots do not. By exploring such functions, we can figure out a future robot to be definitely necessary and a robot design to avoid failure in practical application. This paper first discusses what is the special skill for human and what is the special one for robots. Also, how human and robots are essentially different from each other? To discuss these issues, we have to know the current state-of-the-art of robot technology from the viewpoint of manipulation. We particularly pick up both dexterity and speed in manipulation based on our former works, M. Kaneko and Tsuji (1997, 2000a); M. Higashimori and Kaneko (2005a,b); M. Kaneko and Tsuji (2000b); M. Kaneko and Ishikawa (2003); M. Higashimori and Ishikawa (2005); M. Higashimori and Kaneko (2007, 2009c,a,b). By comparing these functions for human and robot, we show that human are good at dexterous manipulation, while robots are not. On the other hand, robots are good at speed, power, repeatability, accuracy, and so forth, while human are not in relative sense. Through these reviews, we discuss how we should collaborate with robots, and what skill we should expect and not expect for robots. As a successful example, we introduce a medical robot, da-Vinci developed by Intuitive Surgical Ltd. This company is doing a really good business recently from the viewpoint of stock market, which means that the robot should include something important function. What functions do they include and cut intentionally? Through exploring these questions, we eventually reach answers that we are looking for.

This paper is organized as follows; In Section 2, we consider special skills for both human and robot. Based on this consideration, we propose a collaboration style between human and robot in Section 3. In Section 4, we introduce an example of robot with success story. By analyzing the key function of this robot, we show a direction of future robots in Section V before concluding remarks in Section 5.

2 The Special Skill for Human and Robot

Two examples of highly skillful manipulation done by human are shown in Fig. 1, where (a) and (b) are juggling and manipulation of a pencil by hands, respectively. Perhaps, each person should have practiced for many years to get the skill. Through learning process, human have the potential capability for increasing manipulation skill gradually. There are three key parts to support human dexterity. The first part is finger tip where there are a numerous number of tactile sensing organs Bolanowski and Verrillo (1982); Bolanowski and Zwislocki (1984); Verrillo (1962). While there are four tactile receptors, such as Ruffini ending, Merkel cell, Meissner corpuscle, and Pacinian corpuscle in finger tip, it is well known that each mechanoreceptor is activated with different frequency and contributes to enhancing the touch sensitivity depending upon frequency. For example, Ruffini and Merkel are responsible for low frequency, such as less than 10 [Hz]. Meissner corpuscle and Pacinian corpuscle are responsible for the frequency between 10

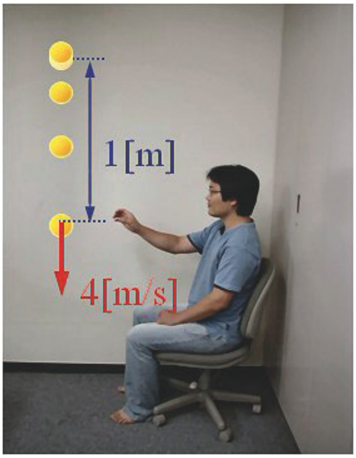

Figure 2. Catching a ball.

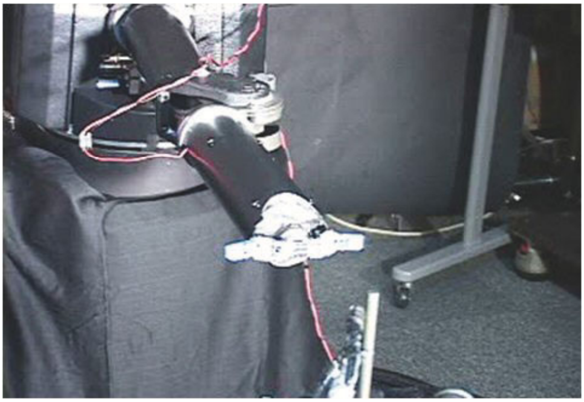

Figure 3. The 100G capturing robot.

through 50 [Hz] and more than 50 [Hz], respectively. They can detect not only pressure but also velocity and acceleration. We believe that these receptors are greatly support the dexterity of manipulation by human. The second part is our powerful brain having the function of learning and keeping data based on experience. Based on the information coming from fingertip tactile organs and on data base, our brain sends a command message to muscle quickly. The third part is our flexible and powerful muscle. The

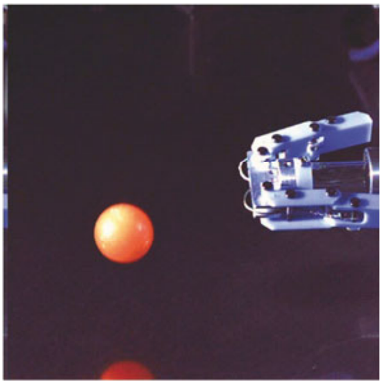

Figure 4. A few mmseconds before the hand captures a ball.

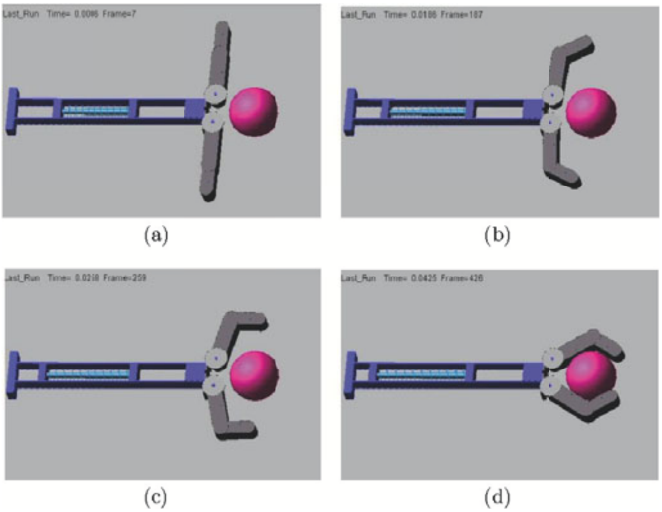

Figure 5. Simulation results for capturing an object.

muscles actuating each finger joint are distributed around the fore arm and produce the grasping force with more than 50 [kg]. Compliance is an essential key word for supporting dexterous manipulation. Furthermore, we should not forget that each finger tip has two compliance components; one is passive compliance coming from skin inherent compliance, where we can not change intentionally and the other is active compliance coming from

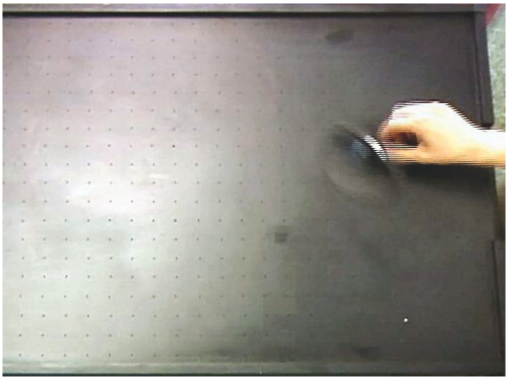

Figure 6. A subject is capturing a moving object.

muscle, by which we can control finger tip compliance intentionally. On the other hand, now let us observe the dexterous motion done by robots. We would note that while there have been a number of multifingered robot hands developed so far M. Kaneko and Tsuji (1997)–M. Kaneko and Tsuji (2000), the dexterity of robots is too behind that of human. Even with DLR hands DLR; workshop, which is probably one of the most sophisticated robot hands in the world, they are not as dexterous as human hand. The main reason why the dexterity of robot hands is so behind of human perhaps comes from their hard mechanism, lumped actuators, and sensors with low resolutions. While manipulation theories have been very much advanced with beautiful mathematics K. Harada and Tsuji (2000); M. Svinin and Tsuji (1999), the advancement of hardware has been too behind them. Successful hands are limited to uni-purpose ones, such as grippers which are familiar as an end-effector often utilized in industry.

While robots are too behind human in terms of dexterity, they have various fields where robots exceed human capability, such as speed, power, accuracy and so forth. We have done a couple of experiments for examining whether human can generate the motion for an object moving with a high speed. Fig. 2 is the first example where a subject is catching a ball dropped from 1 [m] height In this experiment, we ask a subject not to look up the object but to look forward naturally. We further ask the subject to take a catching action when the ball is within his viewing area in natural posture. For this experiment, no one could not catch the ball successfully, even through the ball passes through just the center of hand being in ready for catching. It takes 0.2 through 0.4 [sec] until finger motions start, while

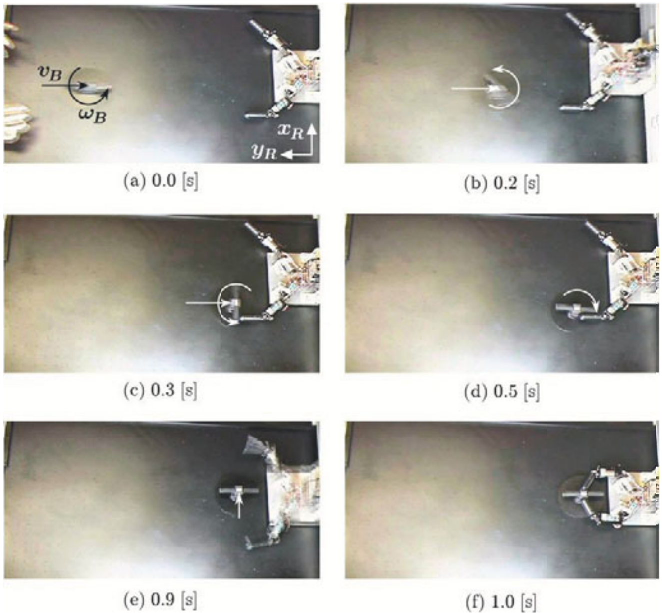

Figure 7. Two-fingered hand captures an object by 2-step strategy.

the speed of object results in roughly 4 [m/s] when the ball reaches at the position of hand. This means that the ball moves 80 though 160 [cm] at the capturing point. Therefore, it is essentially impossible for human to capture the ball without feed-forward action. To challenge this test by robot, we developed the 100G capturing robot M. Kaneko and Ishikawa (2003); M. Higashimori and Ishikawa (2005) where G denotes the gravitational acceleration. Fig. 3 shows the experimental result where the robot is successfully capturing a ball with an assistance of a high speed vision system developed by Ishikawa and Ishii T. Komuro and Yoshida (2003); Ishii and Ishikawa (1999); Numata and Tajima (2004); K. Tajima and Ishii (2004). Fig. 4 shows a snap shot where the scene is just a few milliseconds before catching a ball by the hand with one degree of freedom and Fig. 5 shows simulation results where the 100G robot hand is capturing an object. As far as the motion speed is concerned, the 100G robot has exceeded human capability. Due to this high acceleration, human can not see what is actually happening during mechanical adjustment. Due to this high speed, we can not adjust for the best wiring without an assistance of high speed camera. Fig. 6 shows another experiment where a subject is catching an object with

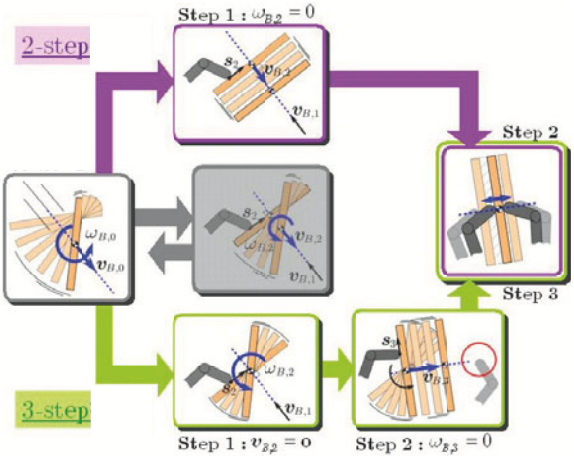

Figure 8. 2-step and 3-step strategies.

both rotational and translational velocities, where the object is moving on an air hockey table whose friction is drastically reduced by air flow. Since the recognition speed of human eye is roughly 15 [frames/sec], the subject can not clearly see the capturing point by his naked eye. To challenge this experiment by robot, we developed the two-fingered robot hand equipped with a high speed actuator for each joint. Under the assumption that both collision and friction coefficients are known in advance, this robot can completely stop either the rotational or translational motion of object at the initial collision with an assistance of a high speed vision, where the vision is always chasing the object and sending both position and orientation of object to the robot controller. We also showed that this robot can capture an object successfully after one or two collisions as shown in Fig. 7, while human can not do M. Higashimori and Kaneko (2007). For example, in two-step capturing strategy, the object results in a translational motion with constant posture to be easily captured by the robot as shown in Fig. 8 where three-step capturing strategy is illustrated as well. In this sense, this robot also exceeds human capability. Fig. 9 shows a further example, where a pizza master is manipulating a pizza dexterously by utilizing a tool composed of just a simple plate and a rod. An interesting observation is that he can manipulate a pizza rotationally as well as translation ally, by utilizing both friction and acceleration forces with a proper combination. By getting a hint from this observation, we figure out a robot system as shown in Fig. 10 where a humanoid robot is manipulating a plate, just like

Figure 9. Manipulating a pizza by a master.

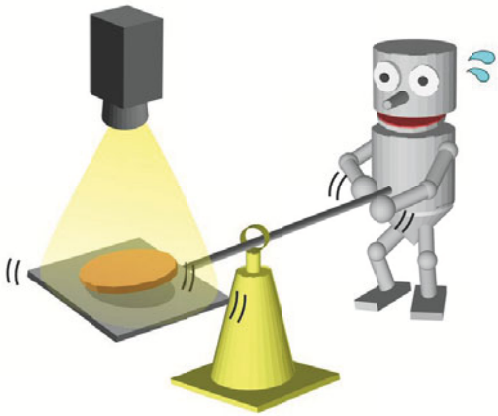

Figure 10. An example of pizza manipulation robot.

a pizza master. However, this approach will not work well, since a dexterity which is not good at for robots is requested. To cope with this issue, we have developed a robot with two-degrees of freedom M. Higashimori and Kaneko (2009c) instead of a humanoid robot. By combining a high speed vision, we have achieved various experiments, such as rotational as well as translational motions of object on the table. Also, we have done manipulation of the object from the starting point to the goal setting on the table. This

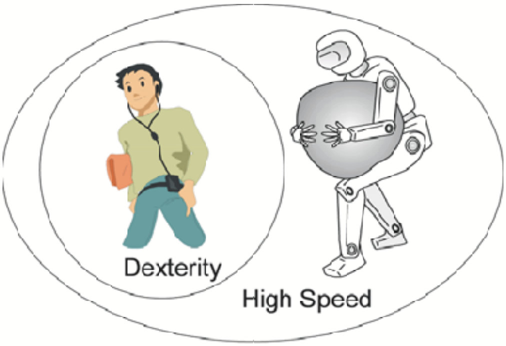

Figure 11. A possible style of collaboration between a robot and human.

robot can achieve the manipulation task less than just 10 [sec], while human can not do it even with more than 1 [min]. In such a scene, this robot also exceeds human capability. In our recent work M. Higashimori and Kaneko (2009a,b), we have shown that the pizza robot can rotate a compliant object just like a pizza before cooking even faster than a rigid one. These three examples suggest that by combining both high speed actuators and a high speed vision system, as far as speed is concerned, robots have already exceeded human capability. Therefore, we are now in a state where robots are too much behind human in dexterity and advanced more than human in speed. In collaboration between robots and human, we should consider this fact.

3 A Collaboration Style between Robots and Human

Many researchers have shown a collaboration style where both human and a robot achieve an equal task. This is based on the idea that we expect an equal skill for both human and robots, which is a big mistake at the starting point. As explained in the previous section, there are different special skills for human and robots, respectively. Human is good at dexterity whose skill is even more than the current robots. On the other hand, robots are good at a simple task with high speed. As for a collaboration style between robots and human, we should take these special skills into consideration. Fig. 11 explains a possible collaboration style where we expect dexterous motions for human and high speed simple motion for robots, respectively. We believe that this is a reasonable collaboration style between them. Now, let us consider an example of this style. Suppose that a medical doctor is operating a patient under minimum invasive surgery. He should be good at in dexterity by his long term training. On the other hand, however, human have a limitation of recognition speed of human eye. It is well known that the limitation is roughly 30 [ms] in the maximum. This limitation can not been overcome by practice, while your skill for dexterity gradually increases by continuous practice and learning. Now, suppose that a medical doctor cut a blood pipe just by accident. At the next moment, the blood will spread over the area where he is looking. Since this happens very quickly, his eye can not follow and eventually lose where the accident part is. Here, we suppose that the medical system is equipped with a robot with high speed vision and always watching the motion area of forceps. At the moment he cut a blood pipe, the robot takes action for stopping the flow of blood based on the information of the high speed vision. This is a good style for the collaboration, in a sense that the robot is compensating for the function where human is lacking.

4 A Success Example in Robot Business

While an entertainment can be one of business fields of robotics, it is fade away quickly when people are tired with the robot. Robot history has proved that this is true. Is there any success example in robot business except industrial robots? While there have been a number of robots designed and developed so far, we do not know many examples where the company is doing a good business continuously through robot. da Vinci developed by Intuitive Surgical Co. Ltd. Vinci (a,b) is probably one of very rare examples where the company is doing a really good business as far as we check the increase of the price of stock during the last five years. While the price is $2.5 million/robot, they have sold out more than 1500 robots all over the world. Why this robot is so popular? Why hospitals are buying this robot? Through exploring these questions, we try to find the answer for the question given in the title of paper. I believe that da Vinci will be never fade away, because this robot is so useful for human. For example, more than 70% operation of prostate cancer in US are currently done by this robot. The operation of prosthetic cancer needs dexterous manipulating motion behind the bundle of nerve system. So far, it has been really hard for a surgeon to insert a forceps manually and cut a tumor without giving any damage to the bundle of nerve system around the cancer area. With the reacheability to the back side of the bundle of nerve system, da Vince successfully showed its unique function all over the world. Now, let us discuss the design policy of da Vinci. Fig. 12 shows an overview of da Vinci system where a surgeon remotely controls the robot based on the visual

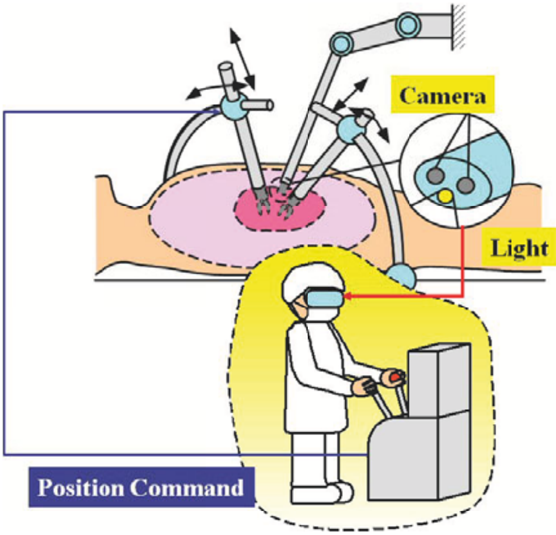

Figure 12. An example of medical robot system.

information obtained through 3D stereo image. Fig. 13 shows two possible end-effectors available for medical robots, where (a) and (b) are a gripper type hand and a multi-jointed hand, respectively. The biggest attractive function for multi-jointed hand is the potential capability of manipulation of object within the hand, while this function has never been practically utilized in either industry or medical field. In manipulation of object within a hand, robots are too behind human, as discussed in Section II. The designers in Intuitive Surgical cut this function from da Vinci and adopted a simple gripper type hand, as shown in Fig. 13(a). Nevertheless, it looks that da Vinci is achieving dexterous and skilful manipulation by using two arms. The key is that each gripper simply grasps the object, such as a needle, a thread, or internal organ, and a surgeon produces a gripper level coordination control through a master arm. The dexterous motions are, therefore, produced by the degrees of freedom of arm instead of finger. Once again, we should note that the dexterity of da Vinci is not produced by the finger motions but by the arm motions, together with master motion produced remotely by the surgeon. As far as we carefully examine da Vinci, their approach is quite naturally accepted in terms of the collaboration between human and robot. Also, we would completely agree with their decision for cutting the function of multi-jointed finger.

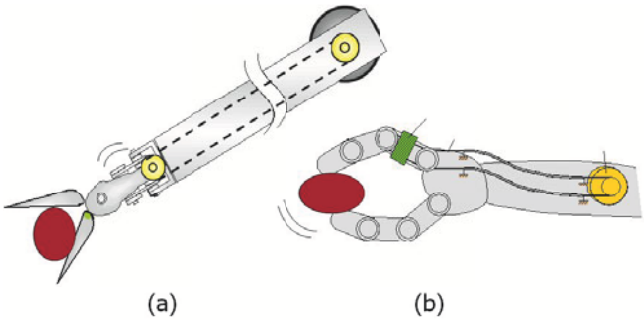

Figure 13. Two types of hand for medical application.

5 Where Future Robots should Go and should not Go

da Vinci is sending us a couple of important messages on future direction of robot. While so many innovative mechanisms are, of course, implemented into the robot, such as a wire driven gripper, an easily detachable hand according to wire damage during operation, and so forth, we believe that one of the best decision in design is to cut the choice of multi-jointed fingers and to produce dexterous motions by multiple arm coordination control by surgeons. The success of da Vince implicitly sends us a message that for robot design, we should not include a function of manipulation of object within the hand by utilizing multi-jointed robotic fingers, if we try to keep a high success rate in practical use, such as medical and even for industrial applications. Also, da Vince eventually succeeded in finding the task where only this robot can successfully remove a tissue of prostate cancer without giving any damage to human body.

6 Concluding Remarks

We have discussed the direction of future robots from the viewpoints of manipulation. Human hand is a universal tool for manipulating a knife, a spoon, a folk, a pencil, and many others. With this similarity, people are expecting that multifingered robotic hands will be available as a universal end-effector for future robots. But it is actually too difficult to design and develop a multifingered robot hand available with a reasonable reliability in a practical environment. We explained the difficulty of dexterous manipulation by comparing the difference between robots and human. Especially, the difficulty of manipulation of object within the hand comes from that we are allowed to use a set of pushing forces only. The smooth and quick motion of object is also blocked by many physics, such as, slipping, rolling, and instability due to a large pushing force on object. The success story of da Vinci is sending a message toward a practical solution. Instead of designing a complicated hand system, we should design a hand as simple as possible. We believe that it is important to rearrange the manufacturing line, so that a single purpose hand may work in it with firm reliability.

Imitating living things is a well known approach for designing a robot. But we have to be careful that both artificial machines and living things are far different from each other, in terms of actuator, sensor, and even mechanism. Human fingers have continuously evolved through the process in using various tools for long long periods since making appearance, and eventually became a universal one. We should not expect such a universal hand for an artificial one. Over 30 years have passed already since many projects on multi-fingered robotic hand have been launched. At least, the research results on multifingered robotic hands so far have supported our messages without any counterexample. We are now in a state where we should send many robots working in various environments. In concluding, we would note once again that we should not devote our power in designing a human finger-like universal hand for a future robot hand, if we would see a robot system capable of working practically. We are more than happy if this article is helpful for researchers wishing to design a hand in the future.

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Robust Drives for Parallel Robots

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Abstract Parallel robots are known to offer light, highly agile structures, particularly suited for assembly and machining tasks. By the same token, parallel robots pose unique challenges to the robot designer, in that a compromise must be found among the various requirements: large workspace with respect to footprint; high stiffness; high natural frequencies; high mobility; and low cost, among others. Most parallel robots are designed with as many limbs as degrees of freedom (dof), which increases their footprint and limits their dextrous workspace—that region of the workspace where the moving platform can undergo a full rotation. An alternative to these designs is a reduced number of limbs, lower than their dof, but this calls for limbs driven by two or more motors. The challenge here is to drive two axes in a serial array with two motors mounted on the base platform. This mode of driving has not received due attention from the robot-design community, but is worth exploring. Proposed in this paper is a *quasispherical* linkage intended to drive the tilt axis of one of the two limbs of a four-dof parallel robot, currently under development. The linkage is termed quasispherical in that it is nominally designed as a spherical four-bar linkage, but spherical linkages impose extremely tight tolerances to make them assemblable. A common alternative to tight tolerances is an increase in the degree of freedom of the linkage, upon replacing the passive revolutes by orientable pinned-joints, which are kinematically equivalent to spherical joints, thereby increasing unnecessarily the mobility of the linkage. This compromises the linkage stiffness, a major concern for effective actuation. As an alternative, a linkage of the RCCC type is proposed here, where R and C stand for revolute and cylindrical joints. However, cylindrical joints are not that common as machine elements, besides being demanding in terms of tolerances, while offering low stiffness. A realization of the C joint is proposed here by means of a serial array of a R and a screw joint, labeled H.

1 Introduction

SCARA (Selective-compliance Assembly Robot Arm) systems were developed in the eighties with the purpose of providing the manufacturing industry with agile robots capable of fast pick-and-place operations of flat workpieces, as those appearing in the consumer electronics industry (Makino and Furuya, 1980). In the late nineties, these robots had reached their physical limits, with cycle times reported by Adept Technology Inc. of 50 ms for an industry-adopted test cycle (Gauthier et al., 2008). Higher speeds would be possible only with larger motors, but these would impose correspondingly higher loads on their downstream counterparts. The obvious alternative was parallel SCARA systems. This is how several parallel architectures for the production of motions proper of SCARA were developed—e.g., (Company et al., 2001; Angeles and Morozov, 2006). Company et al.'s patent is currently marketed by Adept Technology Inc. under the trademark *Quattro*. This robot entails four limbs, each driven by one base-mounted direct-drive motor, the design challenge being how to allow the moving platform (MP) to undergo rotations about a vertical axis of at least 180°, as required by the manufacturing industry. The solution proposed by the designers of Quattro entails an ingenious mechanism composed of linkages and gears that does the job, at the expense of a large number of moving parts. The robot architectures patented by Angeles and Morozov (2006), termed *Schönflies Motion Generators* (SMGs), entail either four or two limbs. The McGill SMG motivating the work reported here is an instance of the latter, with two limbs, each driven by two identical motors mounted on the base platform (Morozov and Angeles, 2007).

A design challenge posed by the McGill SMG lies in the need to drive two axes in a serial array by means of two motors mounted on the same base platform. Of these two axes, one is vertical, producing the *pan motion* of the plate carrying the upper parallelogram of each limb, the other horizontal, producing the *tilt* motion of the parallelogram itself. The drive of each limb comprises a planetary gear train, as depicted in Fig. 1, whose sun and ring gears are driven by means of two identical motors, at angular velocities ω_S and ω_R, respectively. The output angular velocities of the train are the angular velocities of the planets and the planet-carrier, the latter being the pan angular velocity of the drive. The tilt angular velocity is to be taken from the *relative* (vertical) angular velocities of the planets with respect to their carrier, and hence, a conversion from an angular velocity about a vertical axis to one about a horizontal axis, preferably with a ratio of 1:1, is required. This design problem is the motivation behind the linkage proposed here. However, this problem arises also in the driving of a six-dof parallel robot designed with three limbs, as opposed to six, which is the common design known as Stewart-Gough platform (Merlet, 2006). In a three-limb design, each limb has to be driven with a two-dof actuator, its two motors preferably a) mounted on the base platform and b) subject to identical loads. An obvious mode of driving in this case is also a pan-tilt mechanism, similar to that introduced here.

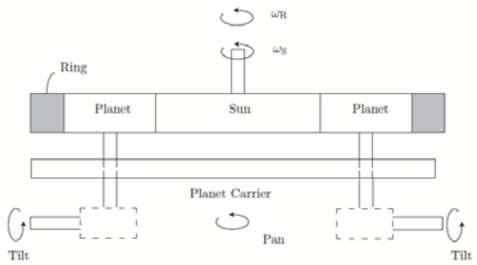

Figure 1. The two-dof limb-drive of the McGill SMG: a planetary gear train

The paper focuses on the synthesis of the transmission from planet axes to tilt axis, which is henceforth termed the *tilt-generator*.

2 Alternative Designs of the Tilt Generator

Four alternative design solutions were considered for the tilt-generator: 1) a bevel-gear train with input and output axes at right angles; 2) a double universal joint; 3) a five-link mechanism; and 4) a spherical four-bar linkage.

Alternative 1 appeared attractive because of the readily available, off-the-shelf, *right-angle gearboxes* (RAG) and their low cost. The McGill SMG prototype was built with these transmissions. As the planetary train of each drive unit comprises two planets, two RAG were installed per drive, which would distribute uniformly the load on all connected elements. Backlash in the bevel gears was expected to be reduced by the presence of actuation redundancy. As it turned out, however, after assembly, the RAG backlash was still too high, of about 4°. This backlash led to large vertical displacements of the MP, of about 300 mm, with all four motors blocked. An in-depth study was then conducted to find the best alternative out of the remaining three in the above list.

Work currently underway by the same design team[1] on the development

[1]The team in charge of developing the McGill SMG

of a theoretical framework for engineering design at the conceptual stage—i.e., in the absence of a parametric mathematical model—was applied to select the best design alternative. The framework is based on the concept of *complexity* (Khan et al., 2007; Caro et al., 2010). A complexity analysis of the three alternatives of interest, in fact, called for a revision of the paradigm proposed by Khan et al. in 2007. The details of the complexity evaluation of the three alternatives are available in (Khan and Angeles, 2010). The result was that, while the spherical four-bar linkage is unable to produce *exactly* a 1:1 constant velocity ratio between input and output axes, it is the simplest solution from a kinematic viewpoint. The ripple in the velocity ratio can be readily taken into account by means of kinematic control, which calls for the online inversion of a posture-dependent 2×2 Jacobian matrix mapping the two-dimensional array of input velocities—ω_S, ω_R—into its counterpart array of output velocities—ω_{pan}, ω_{tilt}

3 The Tilt-generating Spherical Linkage

A spherical four-bar linkage, with input and output axes at right angles, is depicted in Fig. 2, to illustrate the notation used in the paper. An *approximate function-generation* synthesis approach was adopted (Liu and Angeles, 1992), with m prescribed pairs of input-output angles, to determine the unknown linkage dimensions α_2, α_3 and α_4 of Fig. 2, as $\alpha_1 = 90°$ is given from the layout of the input and output axes. Moreover, given the *symmetry of the functional requirement*, a *symmetric linkage* was assumed at the outset, with $\alpha_4 = \alpha_2$. The problem was then formulated using a set of dimensionless linkage parameters $k_1, \ldots, k_4$ similar to those proposed by Freudenstein (1955) for planar linkages, namely,

$$k_1 \equiv \frac{\lambda_1\lambda_2\lambda_4 - \lambda_3}{\mu_2\mu_4}, \; k_2 = \frac{\lambda_4\mu_1}{\mu_4}, \; k_3 = \lambda_1, \; k_4 = \frac{\lambda_2\mu_1}{\mu_2} \equiv \frac{\lambda_4\mu_1}{\mu_4} = k_2 \qquad (1)$$

where $\lambda_i \equiv \cos\alpha_i$, $\mu_i \equiv \sin\alpha_i$. With this formulation, the synthesis problem leads to an overdetermined system of $m > 4$ linear equations in the four parameters k_i, derived from the input-output function

$$F(\psi, \phi) \equiv k_1 + k_2\cos\psi + k_3\cos\psi\cos\phi - k_4\cos\phi + \sin\psi\sin\phi = 0 \qquad (2)$$

Furthermore, in view of the prescribed value of α_1 and the symmetry assumption, $k_3 = 0$ and $k_4 = k_2$, the number of unknowns thus reducing to only two, k_1 and k_2. Additionally, the zeros of the input and output dials were assumed to be placed at undetermined values of α and β, respectively.

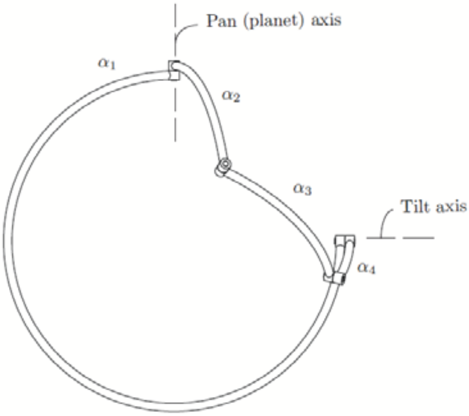

Figure 2. A spherical four-bar linkage with input and output axes at right angles

The m prescribed input-output values were thus defined in intervals $[\,\alpha - \pi/3,\ \alpha + \pi/3\,]$ and $[\,\beta - \pi/3,\ \beta + \pi/3\,]$, according to the relation

$$\phi = \alpha - \beta + \psi \tag{3}$$

A total of $m = 21$ points, evenly distributed over the given intervals, were defined, which thus led to a system of 21 linear equations in the two unknowns k_1 and k_2, with α and β as parameters. The least-square approximation of the given system of equations, for given values of α and β, was calculated over a grid in the α-β plane. The rms value of the *structural error*[2] (Tinubu and Gupta, 1984) $s_{\rm rms}$ was evaluated over the points of the grid, thereby obtaining a set of discrete values of the function $s_{\rm rms}(\alpha, \beta)$. The minimum value of this function was obtained by inspection: minimum occurred at $\alpha_{\rm opt} = 146°$, $\beta_{\rm opt} = 34°$, which yielded $(s_{\rm rms})_{\rm min} = 1.66°$. For our purposes, this value is quite acceptable, as any deviation from the 1:1 ratio between input and output will be taken care of by means of online 2×2 Jacobian inversion. The structural-error distribution is plotted in Fig. 3.

The foregoing optimum values led to a linkage with the parameter values and dimensions recorded in Table 1. Because of space limitations, a rendering of this linkage is not included here. Instead, its quasispherical counterpart is included in Section 5.

[2]The structural error of a linkage is the difference between the output value *generated* by the synthesized linkage and the *prescribed* output value at the same input value.

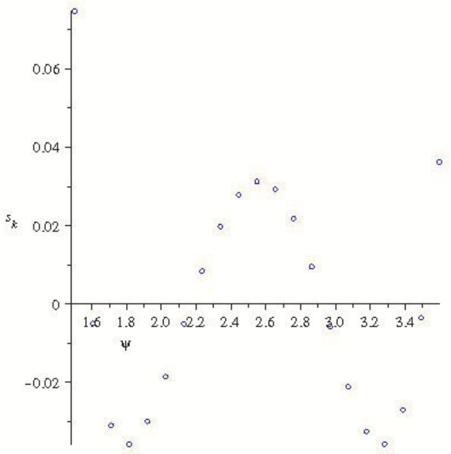

Figure 3. Structural error s_k at kth data point over the prescribed range of motion

i	1	2	3	4
k_i	1.2245	0.90890	0.0000	0.90890
α_i	90.000°	47.731°	132.11°	47.731°

Table 1. Optimum values of linkage parameters and dimensions

One more performance index, besides compliance with the function-generation task, that should be monitored, is the *transmission angle*, which measures the percentage of transmitted torque that goes into actually driving the output joint, vs. the percentage that produces internal wrenches—concurrent force and moment—that put extra load on the bearings and on the link structures (Chiang, 1988). Machine designers recommend to keep this angle between 45° and 135° in planar linkages. For spherical linkages there are no guidelines, but the main idea is to keep the transmission angle close to 90°. As a performance index in this regard, the *transmission defect* δ was proposed (Gosselin and Angeles, 1989), which is defined as the rms value of $\cos\mu$ over the range of motion of the input joint that is of interest for the task at hand. We thus have that the range of values of δ is $0 < \delta < 1$. The optimum linkage reported above has a $\delta = 0.4536$, which is fairly acceptable. This value corresponds to $\mu = 63°$.

4 The Kinematics of the Two-dof Drive

The two-dof drive involves two mechanisms, the epicyclic gear train and the spherical four-bar linkage, its Jacobian, mapping input rates into output rates, thus involving features of the two. If these rates are cast in the two-dimensional arrays $\boldsymbol{\omega}_i$ and $\boldsymbol{\omega}_o$, respectively, then the foregoing relation takes the form

$$\boldsymbol{\omega}_o = \boldsymbol{J}\boldsymbol{\omega}_i \tag{4}$$

where

$$\boldsymbol{\omega}_i = \begin{bmatrix} \omega_R \\ \omega_S \end{bmatrix}, \ \boldsymbol{\omega}_o = \begin{bmatrix} \omega_{\text{pan}} \\ \omega_{\text{tilt}} \end{bmatrix}, \ \boldsymbol{J} = \begin{bmatrix} \dfrac{1}{1+m} & \dfrac{m}{1+m} \\ \dfrac{\nu}{1-m} & \dfrac{-\nu m}{1-m} \end{bmatrix} \tag{5}$$

ν denoting the *input-output velocity ratio* of the four-bar linkage, namely,

$$\nu \equiv \phi'(\psi) = -\frac{\partial F/\partial\psi}{\partial F/\partial\phi} = \frac{k_2 \sin\psi + k_3 \sin\psi\cos\phi - \cos\psi\sin\phi}{-k_3\cos\psi\sin\phi + k_4\sin\phi + \sin\psi\cos\phi} \tag{6}$$

in which the partial derivatives are those of function $F(\psi, \phi)$ introduced in eq.(2). Thus, $\omega_{\text{tilt}} = \dot{\phi}$, while $\dot{\psi} = \omega_P - \omega_C$, with ω_P and ω_C denoting the angular velocities of the planets and the planet-carrier, respectively.

It is apparent from eq.(6) that ν, and hence, $\boldsymbol{J}$, is *posture*-dependent[3], as $\nu = \nu(\psi)$. Hence, the inverse Jacobian, needed for the kinematic control of the parallel robot at hand, cannot be computed off-line. Given the simple form of the Jacobian, however, a closed-form expression for its inverse is possible, namely,

$$\boldsymbol{J}^{-1}(\psi) = \frac{\nu}{1-m}\begin{bmatrix} \dfrac{\nu}{1-m} & \dfrac{m}{1+m} \\ \dfrac{\nu}{1-m} & \dfrac{-\nu m}{1-m} \end{bmatrix} \tag{7}$$

thereby completing the kinematics of the two-dof drive.

5 The Tilt-generating Quasispherical Linkage

The realization of the linkage synthesized in Section 3 is highly demanding in terms of accurate machining and assembly, given that a spherical linkage is an overconstrained mechanical system. Indeed, unless the axes of the four R pairs intersect, the linkage cannot be assembled. Expert designers have

[3] The posture of a mechanical system is the layout, or configuration, adopted by the system when its kinematic pairs undergo relative motion.

coped with this demand by replacing the passive revolute pairs by their *orientable* counterparts, which are kinematically equivalent to S joints. If every S pair is regarded as the serial array of three R pairs of intersecting axes, then the closed chain that originally comprised four joints now has $3 \times 3 + 1 = 10$ R joints. As a single-dof closed kinematic chain needs only seven R pairs to be movable (Hartenberg and Denavit, 1964), the new closed chain has an excess of three joints, which reduces substantially its stiffness. An alternative to this solution is to add the necessary and sufficient number of joints, which can be done by replacing the three passive R pairs by C pairs. If each of the latter is regarded as the serial array of a R and a prismatic (P) pair, then the new closed chain ends up with exactly seven pairs. This solution was implemented verbatim, i.e., with custom-made C pairs as such, in a previous system developed in the same laboratory (Bidault et al., 2001), given that these joints are not readily available in all sizes off-the-shelf. These joints, however, entail a large backlash that mars the system performance.

An alternative realization of the C pair was sought, that would be simpler than that tried above. Using the same complexity analysis mentioned above (Khan and Angeles, 2010), it was found that a HR serial array would yield a C pair with a lower complexity, and hence, we surmise, with a smaller backlash. The result is, then, a seven-joint linkage of the RHRHRHR type, and hence, isostatic. The linkage thus resulting is displayed in Fig. 4. In this figure, it can be appreciated that the four linkage axes are not concurrent at one single point. This makes the drive fault-tolerant, and hence, robust.

Any backlash brought about by this linkage is to be compensated for with redundant actuation: the epicyclic train was designed with three planets, to allow for various alternative driving mechanisms; two of these will be used to drive the same tilt axis of a parallelogram linkage. With this mode of actuation, the load will be evenly distributed between the two planets and on two teeth of the sun and the ring gears, as opposed to only one of each.

6 Conclusions

An innovative fault-tolerant, robust linkage for tilt generation from a vertical shaft was proposed in this paper. The linkage is termed quasispherical because it is designed using a nominal four-bar spherical linkage. The tight tolerances required by spherical linkages, as imposed by the required concurrency of its four axes at one common point, the center of the sphere, are relaxed by replacing the three passive R joints by a RH concatenation. This solution is attractive because all elements needed are readily available as off-the-shelf components, in various sizes and characteristics—from low-cost to

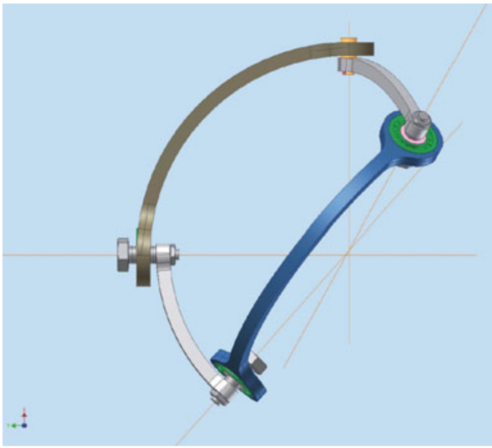

Figure 4. A quasispherical four-bar linkage for tilt-generation with a vertical shaft as input

high-precision.

7 Acknowledgements

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Minimal-Form Multibody Dynamics for Embedded Multidisciplinary Applications

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Abstract Multibody dynamics is a largely explored field in which several successful methodologies and commercial codes coexist. Recently, there is ongoing research in developing efficient, easily embeddable codes that can be used as kernels for multidisciplinary applications. This is triggered by the quest to apply methods developed for robotic systems to systems featuring more complex kinematics. This paper describes two approaches for producing easily embeddable and efficient multibody code based on a minimal-form formulation: an object-oriented approach based on the kinetostatic transmission properties, and a symbolical approach based on regarding kinematical loops as transmission elements. The concepts are illustrated by application examples from industry and research.

1 Introduction

Multibody modelling and simulation is a rich and classical area of research since many years. Starting at early concepts (Nikravesh and Haug, 1982, Schiehlen, 1984, Orlandea, 1987, Rulka, 1990), it has developed to a well-established discipline with major commercial software packages available. Nevertheless, there is still ongoing research in the modelling of kinematics and dynamics of multibody system which is aimed at producing efficient, easily embeddable code (Fanghella et al., 2003, Khan et al., 2005, Lot and Lio, 2004, Brüls et al., 2006, McPhee and Redmond, 2006, Bauchau, 2009, From et al., 2010).

This paper describes some developments performed at the Chair for Mechanics and Robotics of the University of Duisburg-Essen in the area of generation of object-oriented and closed-form solutions for the dynamical equations for multibody systems in minimal form

$$\mathsf{M}(\underline{q})\underline{\ddot{q}} + \underline{b}(\underline{q},\underline{\dot{q}}) = \underline{Q}(\underline{q},\underline{\dot{q}},t) \tag{1}$$

where $\underline{q} = [q_1 \ldots, q_f]^{\mathrm{T}}$ are the independent generalized coordinates, M is the $f \times f$ mass matrix, $\underline{b}$ is the $f \times 1$ vector for generalized Coriolis, gyroscopic and centrifugal forces, $\underline{Q}$ is the $f \times 1$ vector of generalized forces, and f is the degree of freedom of the system. Although such equations can not always be produced for general multibody systems, and a more general approach is the use of Lagrange multipliers, for many actual applications closed-form solutions exist. For such applications, minimal-form formulations prove to be significantly more efficient than the Lagrange multiplier approach, and thus tools for their automated generation can contribute to better formulations and save substantial time of development. The paper briefly describes in the next two sections two main approaches — object-oriented modelling and symbolical equation generation — for this purpose and illustrates in Section 4 the concepts by some applications.

2 Object-Oriented Modelling

The idea of object-oriented programming consists in identifying real-world objects and the processing required by those objects, and then creating simulations of those objects, their processes, and the required communications between the objects (Sebesta, 1989). This paradigm has led to substantial improvements in software design, allowing the application engineer to think in terms of intuitive and familiar notions and reducing substantially the effort to maintain and extend a piece of code. Based on the client-server

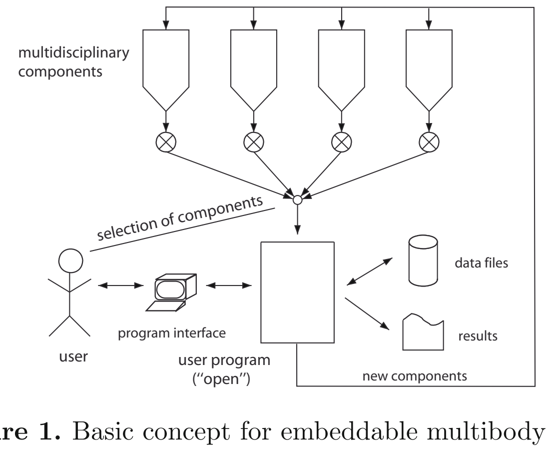


Figure 1. Basic concept for embeddable multibody code.

model (Wirfs-Brock and Wilkerson, 1989), it is possible to define embeddable code that can be mixed with other disciplines such that a user can assemble a problem-specific simulation environment on a case-by-case basis (Fig. 1). This includes numerical algorithms, sensor data acquisition, graphical rendering, interfacing with external devices, and others. In this way, application-specific interfaces can be readily designed which are fast and efficient and at the same time intuitive to the user.

In order to realize the client-server model, one needs to define the mechanical interactions at an abstract level which is independent of the particular internal algorithms used to compute this behaviour. Such an intrinsic view is obtained by regarding a mechanical component as an abstract entity called "kinetostatic transmission element" which maps motion and forces between a set of 'input' state objects and a set 'output' state objects (Fig. 2). Here, input and output state objects can be spatial reference frames and/or scalar variables, including associated velocities, accelerations and generalized forces (Kecskeméthy and Hiller, 1994).

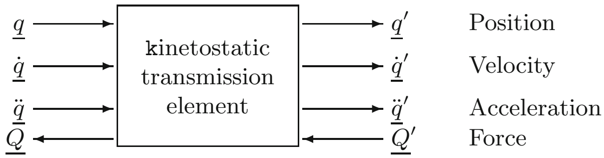


Figure 2. The concept of the kinetostatic transmission element.

The operation of *motion transmission* consists of the three sub-operations

$$\left.\begin{array}{lcl} \underline{\text{position:}} & \underline{q}' = & \underline{\varphi}(\underline{q}) \\ \underline{\text{velocity:}} & \underline{\dot{q}}' = & \mathbf{J}_\varphi \underline{\dot{q}} \\ \underline{\text{acceleration:}} & \underline{\ddot{q}}' = & \mathbf{J}_\varphi \underline{\ddot{q}} + \dot{\mathbf{J}}_\varphi \underline{\dot{q}} \end{array}\right\} , \tag{2}$$

where $\mathbf{J}_\varphi = \partial\underline{\varphi}/\partial\underline{q}$ represents the $m \times n$ *Jacobian* of the transmission element for n inputs and m outputs. Furthermore, a force-transmission mapping can be defined by assuming that the transmission element neither generates nor consumes power, i.e., that it is *ideal*. By equating virtual work at input and output, one obtains the *force transmission* function

$$\underline{\text{force:}} \qquad \underline{Q} = \mathbf{J}_\varphi^{\mathrm{T}} \, \underline{Q}' \quad . \tag{3}$$

which maps forces at the output to forces at the input via the transposed Jacobian.

A general-purpose C++ library termed MOBILE has been implemented which allows also to incorporate impact and limit events (Kecskeméthy, 2003). Here, all relevant computations arising in multibody dynamics are embodied by corresponding individual kinetostatic transmission elements, allowing one to access the transmission functions of a particular component without necessarily knowing which object is actually carrying out these functions. The library includes objects for elastic beams, constraint formulations, closed-loop solutions (both explicit and iterative), inverse dynamics, direct dynamics, optimization, etc. Basically, this corresponds to a view of dynamics as differential-geometric mappings between metric-endowed manifolds expressing coordinates at different modelling levels (rigid-body motion, joint variables, generalized coordinates, constraint measurements) and including metric and force pull-back transformations between them (Kecskeméthy, 1994). By the object-oriented approach, the library can be easily extended, as was done for example to incorporate interval analysis in kinematics and dynamics of closed-loop systems (Auer et al., 2008).

3 Symbolical Code Generation

Another approach for producing embeddable multibody code is to generate symbolical solutions. For simple systems like a pendulum or a planar four-bar mechanism, it is evident that a closed-form solution is the most efficient option, which is why in applications such solutions are always hand-coded after formulating them with pencil and paper and then inserted in the overall model. For more complex mechanisms, however, erroneously it has been assumed that closed-form solutions are not possible or too cumbersome to obtain and that thus iterative solutions must be used. However, by regarding the individual kinematical loops as transmission elements termed "kinematical transformers", it is possible to decompose general multiloop system in a series of interconnected kinematical transformers. In the cases where the individual loops allow for a closed-form solution and the interconnection of the kinematical loops allows for a recursive solution flow too, the complete kinematics can be solved in closed form, leading to an iterative-free formulation (Kecskeméthy et al., 1997).

The concepts discussed above have been implemented in a package called SYMKIN based on the symbolic processing language Mathematica (Fig. 3). The package is fully automated and includes, for spatial and/or planar systems, (1) detection of smallest loops by graph-theoretic methods, (2) generation of closed-form solutions in single-loop mechanisms where possible (Kecskeméthy and Hiller, 1992), (3) identification of the optimal solution flow in order to recognize recursively solvable systems, (4) generation of relative and absolute kinematics at position, velocity and accelration level, (5) generation of force transmission, and (6) generation of the equations

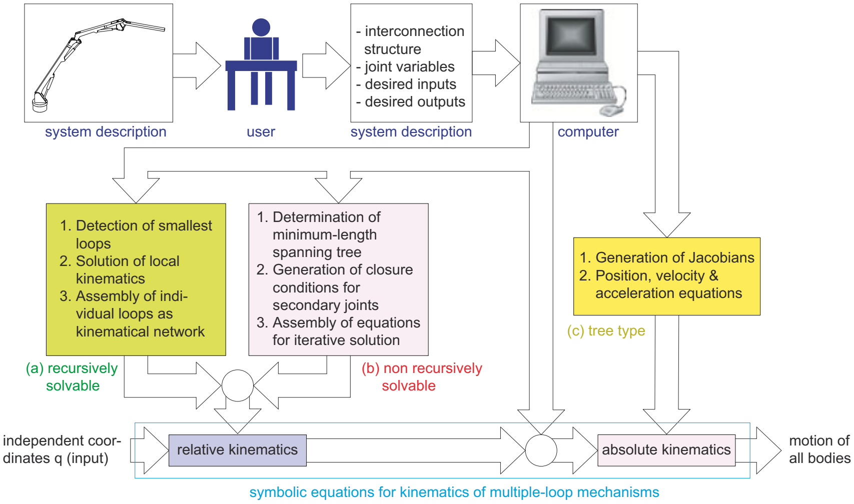


Figure 3. The symbolical equation generation package SYMKIN.

of motion in minimal form. The user just needs to define the kinematical structure of the system and which quantities are of interest. The system automatically recognizes planar subsystems and reduces the computations correspondingly. As the equations are coded by internal variables and elementary kinematical operations, it is easy to export the code to any other language such as C++, graphical processing units, assembler code for micro controllers, etc. by an appropriate back end.

4 Application Examples

In this section, the previous notions are briefly illustrated by some applications. As a first example, consider the design of industrial roller coasters. Here, the aim is to establish a spatial track such that a number of conditions (e.g. geometry of ground and premises, acceleration and force constraints, dimensioning of lifts, drives and brakes, block times, etc.) are fulfilled. Such roller coasters can have quite large tracks (up to 400m) with several figures, so that their design and manufacturing is costly. As the evaluation of the design criteria involves a complete dynamic simulation over the whole track, automatic optimization of the whole track from scratch is not possible. Hence the designer must be able to edit the track (translation and rotation) in terms of experience, and to combine this with automated optimization, without spoiling already polished segments. Moreover, rolling friction, air resistance and spatial moments of inertia parameters have to be modelled and validated in order to obtain realistic motion predictions. Finally, the program should produce automatically the manufacturing instructions for the bending machine of the track.

Figure 4. Example of an industrial roller coaster track.

In order to solve this problem, a "spline joint" was designed offering position, velocity, acceleration and force transmission for a slider along a curved path (Fig. 5). As the orientation information is also relevant and

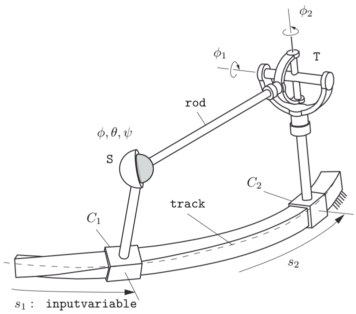
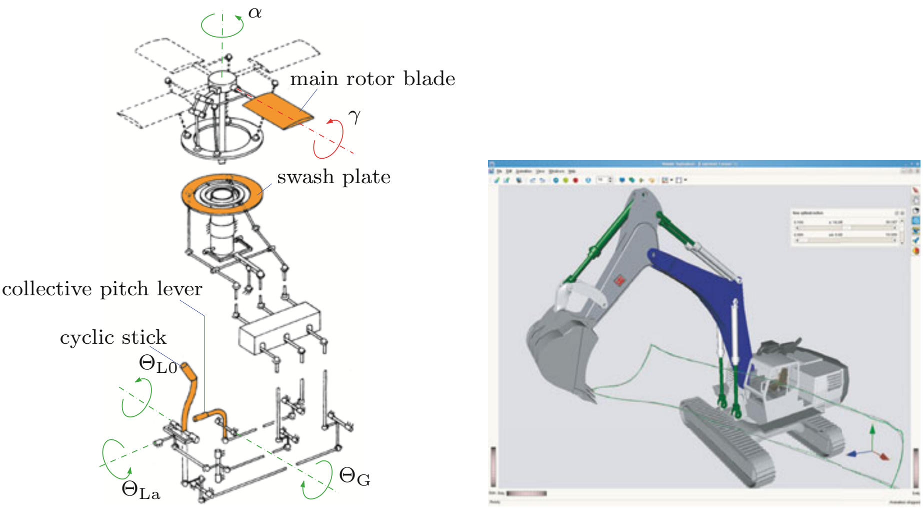


Figure 5. The concept of a spline joint and its use in kinematical loops.

one needs the second time derivative of the rotation for the dynamics, a spline of order five was chosen (Tändl et al., 2007). The spline was globally smoothed using the library of Dierckx (1993). By wrapping the code of the spline joint as a kinetostatic transmission element, the spline joint could be used as a simple joint, i.e., it was possible to use several spline joints in a loop and to resolve one spline joint as a function of the other. By this it is easy to model trains of roller coaster cars on the track. The overall design environment allows for automatic optimization and local editing. One can choose and mix spline joints of three different parametrizations for key frame computations: Frenet, Darboux and Bishop. It is also possible to make copies of the spline objects and to link them together in master-slave mode. By this one can edit the heart line and the three circular rails are generated automatically. With this environment, the design cycle could be reduced from six months to about two weeks, as has been now verified by several industrial roller coasters. It is obvious that the implementation of such an application-specific environment would not have been possible using monolithic multibody . Moreover, the designed objects for spline joints can now be used for general spatial path planning of robots and machines.

The use of closed-form solutions is illustrated for two examples shown in Fig. 6. The one to the left is the main rotor control mechanism for the



a) rotor contro mechanism b) mining excavator

Figure 6. Examples for systems with complex kinematics.

helicopter BO105, the one at the right is a mining excavator (Geu Flores et al., 2007). Both systems have only four degrees of freedom, but several bodies and joints. Both kinematics can be solved in closed-form. The excavator system has the property that the complete subsystem of the arm is planar, while the points move in three dimensions. For both systems, the closed-form kinematics were generated automatically with SYMKIN.

	MOBILE (numerical)	SYMKIN (iterative)	SYMKIN (closed-form)
main rotor	1.00	4.45	31.12
excavator	1.00		8.22

Table 1. Relative computational times for the examples of Fig. 6.

Table 1 shows the relative efficiency of a numerical model in MOBILE, a symbolical iterative model in SYMKIN, and a symbolical closed-form model in SYMKIN for the main rotor mechanism, and the first and last model for the excavator model. One clearly sees that closed-form solutions substantially reduce the computational time. Hereby, it should be noted that the numerical MOBILE code is already faster than numerical Lagrange-multiplier codes (Xia and Kecskeméthy, 2010). By the reduced model, it is possible to easily apply concepts from robotics to the excavator, such as manipulability, path planning, force workspace, etc.

5 Conclusions and Acknowledgements

The paper describes two frameworks for producing embeddable minimal-form multibody code for multidisciplinary applications. The object-oriented framework allows one to combine mechanical elements with other disciplines and to rapidly design application-specific simulation and design environments. The symbolical approach allows one to produce highly-efficient code that can be used e.g. for controllers or within an optimization loop. Both frameworks have the advantage that methods derived for robotics can be easily extended to more complex structures, as the models are automatically generated and their use is as simple as the models of classical robotics. Although not all mechanical structures allow for a formulation in minimal form, this case is very common for actual designs and thus is of interest. The extension of the approaches to Lagrange multipliers and the corresponding numerical solution schemes for differential-algebraic equations is straightforward. Also, the object-library has been extended to biomechanics where it is being coupled with MRI measurements, 3D rendering and computerized diagnosis tools (Ambrosio and Kecskeméthy, 2007, Raab et al., 2009).

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