Challenges in Contact-Support Planning for Acyclic Motion of Humanoids and Androids

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***Abstract*—In order to enhance whole body motion capabilities of humanoids or androids, we study the whole-body contact planning and motion generation problem which allows them taking supports by contacting any possible location on any of their parts, with any permissible location of their surrounding environment. Here, the environment is seen both as (i) a supporting mean, on which supporting motion contacts can be formed and generated, and (ii) an obstacle to be avoided for the remaining parts of the robots –that are not in contact– during the transition motion between two successive contact configurations. This problem can be seen as the generalization of walking. From our recent developments and experiments of such acyclic motion generation with humanoid HRP-2 [1] [2], we discuss in this paper technical issues that need to be resolved and sophisticated, and what are the possible extensions of this challenging problem.**

I. Introduction

Humanoids and androids are anthropomorphic robotic systems. Their particular design raises various challenging problems. Some of these problems are fundamental and traditionally tackled in robotics research; others are peculiar and inherent to their design and potential applications. Near human-size humanoids such as Honda' ASIMO or Toyota's Partner-robots are targeted toward closed-indoor environments (personal houses, business or commercial buildings...) to serve as personal assistants, human servants or ICT society services providers. Other human-size humanoids, such as recent Kawada's HRP-3, are clearly designed for industrial applications such as large building and construction sites, yards, nuclear power-plant maintenance, etc. Small size humanoids such as Fujitsu's HOAP or Sony's Qrio are targeted for entertainment, robot companion, etc. Those are at the commercial stage of finalization. There are, several other advanced humanoid platforms all over the world, most of which serve mainly a wide spectrum of academia research fields.

Androids are yet at the prototype stage and some are advanced enough to be seen as a nearly final product. Whereas all humanoids' prime function is biped mobility (walking) – and non of them can be considered as such without having this functionality, androids' prime function is the degree of human anthropomorphic resemblance and their *quality* can be measured in a similar way the realism of synthetic graphic images is assessed: the more one is confused to decide whether we are dealing with a robot or a human, the better is the resemblance. None of existing androids are able to walk, they are targeted to reception and communication services.

Humanoids/androids are ideally conceived to be advanced manipulators performing a large variety of tasks in a standalone or collaborative way. They are shaped as human-kind not only for the very reason that our environment infrastructures are shaped according to our physical, mobility, motion, and cognitive capabilities, but also because anthropomorphism can make any person guess easily what s/he might expect from such robots, namely in terms of task capabilities and dexterity.

Whole-body motion mobility is obviously an important function of both systems when it comes to human assistance and service. Considerable amount of research tackled this problem from the planning and the control viewpoints. Efficient and robust walking algorithms have been implemented on humanoid platforms. But for humanoids to walk, footprints planning is necessary. Footprint planning received dedicated attention in robotics and computer graphics [3]; more or less astute solutions have been proposed so far. Combining footprint planning and walking control strategy allow humanoid robots to walk on horizontal flat soil, slightly sloped ground or climb stairs. In most cases, the robot uses only its feet, what reduces the amount of possible motions. Ground motion, such as walking, is realized through physical contact interaction between the robot and its surrounding environment. In simpler words, motion is generated by sequencing different contacts between the robot body and its environment. We humans often use other parts of the body to either help a biped motion (e.g. by increasing stability) or to perform motions that are not possible with a usual upright biped posture.

Our aim is to draw solutions to accomplish similar functionalities on humanoids or androids and increase their motion capabilities in non-structured environments or structured but highly cluttered ones. Therefore, since nearly four years, we are addressing the problem of planning non-gaited acyclic motions allowing robots to take support on any part of the environment with any part of their body. Main results dealing with this specific problem have been already published in [1] and [2] and implemented on the HRP-2 humanoid platform [4]. One part of this paper briefly recalls these results. The remaining presents the challenging technical open problems that need to be addressed to sophisticate non-gaited motion of humanoids on real platform, and what are the possible extensions. Because of the lack of space, we do not review deep fundamental mathematical background behind these problems; this is left for future publications.

II. Background

Several methods were inspired from fundamental robotic motion planning [5] [6], to plan footprints of multi-legged robots [7], robotic humanoids [8][1] or virtual avatars [3]. Extending footprint planning to other terminal points taking support on several (predefined) holds have been addressed first in the context of simulation. In [9], non-gaited motion planning for humanoid avatar is made in several steps. First a precursory planner finds a route using a descent gradient method combined with backtracking to escape eventual local minim (Randomize Path Planning). Then based a finite state machine and a heuristic dictated by the current state, holds are selected or contacts removed from predefined holds on the environment. Because the target application is virtual animation, constraints such as torque limits, balance, contact stability and its unilateral nature have not been considered.

Our problem can find several similarities with the so called *multi-step planning* for free-climbing robots, which has been thoroughly studied in [10] [11]. Fundamental basis have been applied to humanoid non-gaited motion in [12]. An improved version of this work using motion primitives is presented in [13]. In these papers, holds are predefined on both the robots and on the environment; a contact is defined as a pair (hold, robot terminal point). Each contact stance (possible contact) forms a constraint manifold. Additional constraints on a given manifold reduce its feasible space. Possible transitions between two successive contact stances have direct mapping in the non-empty intersection between neighboring manifolds' feasible spaces. A stance transition and component graphs are build, pruning of which allows to find possible contact transition. This methods is a contact before motion planning and are clearly close to what we adopted in our approach.

We propose to further extend this work to allow contact supports to occur on any parts of the humanoid/android with any part of the environment. Contrarily to what can be assumed in [10], the problem is not simpler relatively to considering a numerable set of holds that can be contacted by a numerable set of terminal-points. Indeed, a motion before contact approach will not be able to solve our problem (even though, it can substantially reduce its complexity). Indeed, a large possible contact configurations set implies high combinatorial and complexity in the choice to be made. This also different from manipulation planning [14], which also solve the problem by stratifying the configuration space. Our approach uses motion before contact at a first stage, similarly to [9], but with a different approach [2]. We then use this path to drive an incremental building of a contact configurations tree by combining a potential-like best first planning with a posture generator to check the feasibility of each contact configuration by taking into account all possible constraints. See [1] and [2] for technical details.

[1]See also dedicated workshop in the 2007th edidtion of the IEEE-RAS Humanoids conference http://staff.aist.go.jp/kensuke.harada/Humanoids07.htm

III. Some Experimental Results

We performed two major experimental benchmarks on the HRP-2 robot, previously published in [1] and [2].

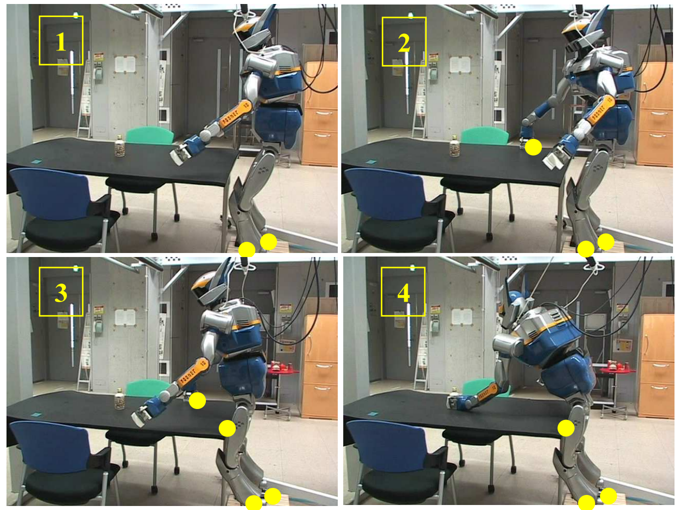

Fig. 1. Contact supports planned for the grasp-can experiment with HRP-2. The yellow circles show the contact in key contact sequences; once the can is grasped, we play the reverse contact sequence.

The first experiment consists for the HRP-2 to grasp a can put on a table. The HRP-2 is put in front of the table and plays the off-line planned sequence of contact-support stances. In this experiment, see key postures in Fig. 1, the planner is guided and generates a plan resulting for HRP-2 to contact first its right hand on the table (sequence 2), then HRP-2 contacts its left leg with the nearest table edge (sequence 3). At this stage, HRP-2 is having four contact supports: the two feet on the floor, the right gripper and the left leg with the table and is in a statically stable posture. The planner then suggests removing the right arm while stretching the left one toward the can to grasp it (sequence 4), see also [1].

The second experiment is more complex. The HRP-2 is sited on a chair in front of the table and is asked to leave the table and go far from it on the left side. If all the space is explored, the planning would more likely take days to find one contact sequence plan. This is the reason why the planning is resolved in two steps: the first step would generate one or several a rough path or route. Then the second step plans the support contact sequence in the neighborhood and along a chosen path/route. At this stage, the first step is ongoing research and for the time being provided by the user.

Obtained results are thoroughly reported in [2]. We illustrate on the Fig. 2 main key-postures snapshots taken from recording videos. What is noticeable is that the planner finds contact configurations where the robot is asked to put its gripper on the table to be able to release its foot (twice, few steps after it stands up). The planner also finds contact stances where the robot is asked to put its gripper on the chair (twice) in order to readjust its feet while leaving the chair.

These experiments revealed several challenging technical

Fig. 2. Leave table experiment with HRP-2. The yellow disks highlight the HRP-2 bodies that are in contact, the red disks point on bodies that released a contact. The number of yellow disks in each picture is exactly the number of supporting contacts. The sequences are only key postures from the overall experiment described in [2]. Many transitions have not been illustrated for clarity and because of space limitation. Most pictures are having three camera views of a similar sequence: the main camera shot is shown in the main body of each picture. The left-upper small snapshots are the view of the camera put behind the chair at the left of HRP-2. The left-down small snapshots are the view of the camera put in front of the feet on the floor. (a) Initial configuration, the robot is sited on a chair in front of the table. (b) the robot lies right to ensure static balance and releases the left foot contact to replace it more on the left; after what the HRP-2 stands-up lining left and put most of its weight on the left leg (this sequence is not illustrated). (c) keeping the left foot contact, HRP-2 releases the right foot one to place it rearer, between the chair legs and ends with two contacts. (d) The planner suggests HRP-2 to take a support with its left arm on the table (3 contacts), and then performs a sequence of foot replacements illustrated by snapshots (e)(f)(g) and (h); the stances switch between 3 and 2 supporting contacts. (i) HRP-2 releases the hand contact from the table and is supported only by feet contacts. It shifts most of its weight on left one to bring the right leg near the left one (j). In sequences (k) to (p) the planner suggest taking support by the right arm on the chair allowing HRP-2 to switch between 3 and 2 contacts for shifting progressively the left and right legs and then all the robot out of the chair and table (q). Note that the hand support on the chair is made ((k) and (l)), released ((m) and (n)) and made again lefter on the chair ((o) and (p)).

issues and raised new research perspectives that we discuss in the remaining part of this paper.

IV. Technical challenges

All the experiments we conducted so far required several tuning and adjustment to perform correctly. Advanced control techniques can be called in rescue to avoid off-line tricky tuning and trials before experiment. For instance, it took more than two weeks of trial before being able to perform the chair scenario on HRP-2. In order to be able to play directly the contact sequence stances plan on a real humanoid or android platform, a number of basic problems need to be considered. We detail some of them hereafter.

A. Model discrepancies and uncertainties

The contact planner performs on the model of the environment described using mainly geometric properties and dynamic ones when friction and balance are considered. These models are a *necessary and unavoidable simplifications* of the actual environment's model. The model (relative) simplification is necessary in order to perform fast planning computation. This is unavoidable due to the lack of (i) knowledge, (ii) precise acquisition sensing and (ii) unpredictable light changes before and/or during the experiments. For instance, position of the table or the chair may be changed slightly during the experiment when HRP-2 first takes support on one of these movable objects. Consequently, further supports using these objects, especially if contacts are planned on their borders will not match the planned contacts' positions. In the worst case the contact may not be valid at all.

In the first case (slight changes on the positions), robot generated trajectories need to be played using guarded motion techniques [15]. Yet, the trajectory generation for the following contact configuration ($k+1$) needs to be recomputed since guarded motion leads to a slightly different contact configuration/posture (k) relatively to what has been planned. In this case, if the trajectory is generated through optimization techniques [16] [17], it needs to be recomputed for target configuration $k+1$ with different initial conditions at (new modified configuration k). This might be time consuming. In another hand, stack of tasks sequencing such as method proposed by [18] [19] can be adapted to execute with guarded control, but they are local and not optimal. A mix of these two techniques can also be envisaged.

B. Contact stability and haptic sensing

In the chair experiment, although it had several other possibilities, the planner chose only terminal robot bodies equipped with force sensor (i.e. the two grippers and the feet) as support means, once the robot stood up from the chair. In this case guarded motion and contact detection are possible. However, in the grasp-can experiment, HRP-2's left leg contacted the table. But without tactile sensor on the leg, the humanoid was not able to asses whether contact is made or not. Our purpose is to allow HRP-2 to contact any parts of its body with the environment as long as it can help achieving advanced motions or tasks. In this case the humanoid or android will relay on two fundamental capabilities:

1) build *stable and robust* contact formation sets on which the robot can relay during dynamic motion transitions;
2) haptic sensing of contact coupled with embedded vision for guarded motion or low level control recovery

Efficient contact formation can be achieved with good hardware/control coupling schemes. Induced contact's shocks need to be absorbed to not excite non desirable frequencies which may results in loosing already established contacts. In the other hand, the contact planner associated posture generator could contribute to contact stability and robustness by electing good contact formations such as favoring plan/plan contacts and banning others such as point/plan, edge/edge, etc.

To absorb contact impulses, compliance is traditionally needed. There are many ways to achieve contact compliance, yet all can be categorized within three main classes:

1) *Cover compliance* (naturally present on androids and nearly banned in humanoids which are having rigid covers): it consists in covering the robot with a foam material whose properties are chosen according to application and hardware limitation requirements.
2) *Joint active compliance* consists in ensuring robot joint compliance through closed loop control of robot's actuators. A simple way to do so is by extracting filtered contact forces from joint or cartesian desired trajectories. This requires the presence of haptic sensing capabilities and fast low level control.
3) *Passive joint compliance* consists in making the robot comply under external applied forces by hardware design (and not closed loop control). Therefore, response to impulse contacts is fast. These solutions are being investigated in human-centered robotics and applications where robots interact with humans.

Obviously a fourth class of solution is any combination of the previous single ones. We are conducting research toward a solution combining foam covers with active control to deal with this issue. We believe that compliant covers are unavoidable. Indeed, a flexible cover would spread the contact area by fitting as much as possible surface asperities and roughness, this has been used in [11]. In the leg/table boarder contact case a rigid cover would not guarantee a good stability of the contact (plan/edge or point/edge in this case) whatever sophisticated are joint active or passive compliance methods. In this very case, a flexible cover would deform according the table border local shape and spread the contact area of the contact, what would increase the stability and the robustness of the contact formation. Moreover, as far as androids are concerned, soft cover are built-in by design which makes our method more attractive.

There might be humanoid applications where soft covers is not always possible, in such cases active or passive joint compliance could be used in combination with an appropriate roughness texturing of the rigid cover.

Haptic sensing in multi-contact support for acyclic motion is mandatory. The chair experiment would have been more elaborated and refined if HRP-2 was able to detect contact on parts of its body other than the terminal bodies. Haptic sensing modality is crucial for guarded motions and recovery strategies from discrepancies. However, contrarily to actual prototyped solutions, a tactile sensing, similar to that of human (i.e. an artificial sensing skin) does not appear to be required; we are also working on this issue.

C. Balanced dynamic motion between successive contact configurations

Once the sequence of contact supports is provided, a controller is needed to realize whole body dynamic motion of the humanoid/android from a contact configuration to the other, sequentially. At each contact configuration, the posture of the robot is given. The problem consists in generating the motion under several constraints. Examples of such constraints are mainly: keeping desired contact set during the motion, dynamic equilibrium, avoiding non-desirable collisions, avoiding various robot variables' limitations (joints, joint speed, torques, etc.). Off-line, this problem can be solved by local planning combined with optimal motion or control generation techniques. The problem is that, once obtained, the trajectory is not robust to variations of the environment and reactive control. This issue was discussed previously in section IV-A. Recently, we addressed problems of distance computation with a new approach to be used in collision and auto-collision avoidance with nice gradient properties in [20] [21]. The problem remains open as for an elegant formulation of the equilibrium and stability criterion to be used for generating the motion since the ZMP criterion would not apply in our case study. Recent studies [22] show several interesting investigations. Moreover, as already evoked in [2], the HRP-2 stabilizer does not handle non-coplanar contacts. Designing a new stabilizer that would handle the closed-loop compensation from non-desirable motion induced by robot internal or external flexibility (namely if covers are uses), is an open issue.

V. New research perspectives

This section addresses some ideas that are open problems to be addressed as future work.

A. Global path and filtering of contact stances

As stated previously, the planner performs in two stages: a first stage where a global rough path is planed and a second stage where support contact sequences are generated *around and along* this path. For the time being, this path is provided manually by the user, who provides a few key postures defining a piecewise linear curve in the configuration space. Detailed description is provided in [2]. Open investigations related to this problem can be summarized with this simple question: how to automatically plan a guide path for a given application and a given robot?

A way to tackle this problem is to consider the robot as floating and plan for nearly-free collision path. However, the path should be rough enough to be quickly planned while having enough granularities in realism to guarantee quick finding of contact sequences. Indeed, the free-floating robot needs to be constraint enough for the generated path to not imply the robot to fly, to fall or to be trapped into local minima without having the possibility to escape. Also, depending on the application, a path favoring normal walking should be weighted relatively to a path implying climbing or bending. However, even heuristic rules are not easy to set, since they depend a lot on the application context and requirements. We are working toward solving this problem.

Several simulation trials and the chair experiment raised another issue: the presence of *redundant* contact configurations. By redundant we mean the possibility for the plan to generate useless contact configurations that can be skipped, or others that can be slightly rearranged for a better transition between the sequences. This problem is also experienced in planning of biped locomotion [3] where smoothing the path required several iterative filtering stages (path straightening, footprint difference, etc.). In the planning method for manipulation tasks proposed in [23], obtained plan was also post-processed at the path and the velocity profile levels. These methods can not apply in a straightforward way to our case.

B. Support contact planning with held or moving objects

If an object of the environment is held by the robot, the problem can fundamentally be formulated in the same manner. The object can be considered as part of the robot which can use it to form contacts if this is allowed. As for manipulating the object through contact sequencing it on the robot, on the environment or on both, the solution proposed in [14] can basically be extended to these cases study.

All our contact planning simulations and experiments have been conducted with a humanoid/android evolving in a static environment; that is to say, contacts are made on non-moving or non-movable objects of the environment. Consider the problem illustrated in the Fig. 3. The humanoid HRP-2 is asked to climb a stepladder to get inside an attic or a storehouse. Not only the planner should generate appropriate contact sequences to climb through the stepladder, but it should only plan for the sequence of contacts which allow opening the trap door progressively in order to go through it until it completely enters the attic or the storehouse. We assume that the rough path planner is able to find the way through the trap door. The contact planner has, at some point, to generate the sequence of contact points allowing the humanoid/android to cross through it while keeping the trap door open. At this point, note that the planned contacts on the trap door are used for achieving a way

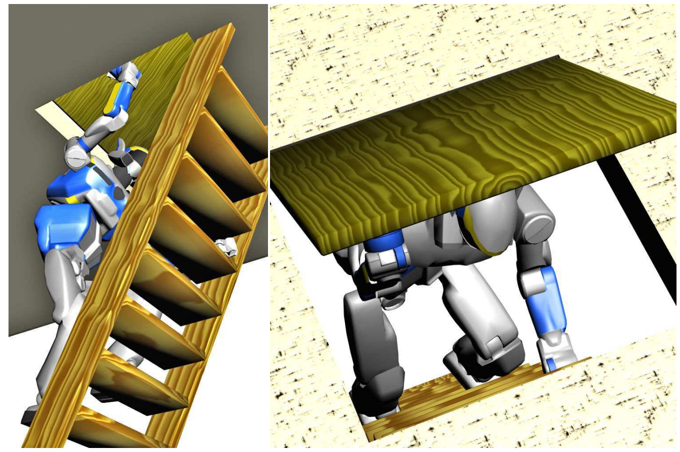

Fig. 3. Generating support contacts to get inside an attic or storehouse. At some points, the trap door needs to be opened while in the same time climbing a stepladder.

out (here in), i.e. opening the door. Likely, they can not be used as a support, since supporting object (here the trap door) is a moving object and the dynamic motion can hardly relay on this kind of contacts to generate stable motion transitions (except in applying forces in directions of constrained motion of the movable object). Seeing the moving object as part of the robot can be considered as an option to reduce the complexity of the problem. However, in this case, unless a grasping hold exists on the trap-door, the unilateral nature of the contact does not allow such a hypothesis. Moreover, here, the best configuration might be to open the trap-door at some point and let it slip on the humanoid back once some parts of it come inside the attic. Tackling such problems is an open issue that we will investigate in future work.

C. Support contacts on deformable environments

Our planner considers only robot made of rigid parts and rigid environments. However, in practice, if humanoids are made, as androids, with flexible covers (see section IV-B) or the environment is deformable, the contact formation, once made, will moves under the motion of the robot. If the deformation is light, the problem can likely be handled as if all was rigid and adapting solution drawn in section IV-A. In the contrary, important deformations require a dedicated approach.

Such a case is exemplified by the Fig. 4. The virtual android is asked to clean the bed's closet, and to reach some spots it needs to take support contact on the bed. The planner may generate the sequence illustrated on the Fig. 4. However, this contact requires taking into account the deformation of the bed to be validated. If the model of the deformation is provided interactively, it can possibly be integrated into the posture generator module. In another hand dynamic motion generation between two successive contact configurations should also enforce contact during motion (since the motion supporting contacts might also move under the dynamics of the motion and that of the deforming environment). Modeling flexibility

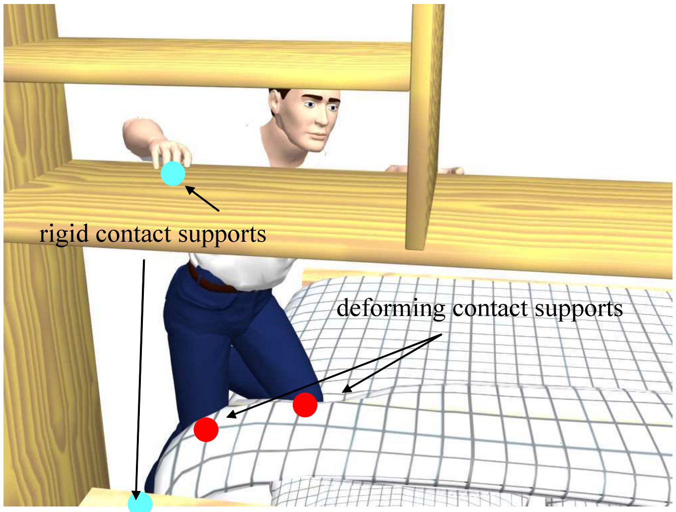

Fig. 4. Generating support contacts in a cleaning bed closet situation. There are two supporting contacts made on a deforming part (here the bed), two others are made on a rigid material (the closet and the floor).

and motion on compliant environment is known to be a very hard problem in robotics.

D. Interactive contact support planning

Interactive contact support planning is useful in humanoid's teleoperation or interactive games with virtual avatars. What differs in this case is the absence of global path. The direction of motion is provided through joystick or various game consoles pad; the contact planner is requested to generate contact support for avatar motion according to the desired direction driven by the user. Here, real-time contact generation with backward and forward capabilities is of prime importance. Moreover, combining simple console or game-box commands, with sophisticated selection of quick contact configurations generation, forward and backwards intelligent functions are the open issues to be investigated.

VI. CONCLUSION

Planning for non-gaited motions extends humanoid and android whole-body motion capabilities. Our approach to this problem [1] [2] proved to be efficient and allowed performing complex experiments using the HRP-2 platform. However, several technical bottlenecks are still to be resolved before reaching a sophisticated implementation. We listed some, such as how to realize robustness of supporting contacts through guarded motion, haptic sensitized flexible cover, and dynamic motion generation between successive contact configurations. We also listed some possible challenging extensions of the problem such as dealing with contact support with movable objects. Future work is dedicated to solve these technical problems and realize the challenging extensions.

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