Toward a Human(oid) Motion Planner

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Abstract This paper outlines our research activities on motion planning and optimization for humanoid and their applications for human motion analysis and understanding. Starting research that applies geometric and kinematic motion planning technique to humanoid robots, we next explored their motion optimization. Although humanoid robots have an anthropomorphic shape and structure, we have first concentrated on dealing with them as robots with many degrees of freedom (DOFs). Studying humanoid robots started drawing more and more interest in human motions: what are their principles when a human make motions? We investigated optimization of walking paths and whole-body motions involving multiple contacts by using criteria and constraints taking into account some features of human motions. We recently focus on complementary investigation on digital human model and humanoid robotics in order to develop tools for product design by reproducing human behaviors, as well as humanoid robots that can work naturally in human environments.

1 Introduction

When a robot moves to one position to another, it needs to change its configuration by avoiding collision with the given environment. Research on this problem of planning robot motion or path from initial to final positions became active from 1980's when the notion of configuration space was introduced and deterministic methods such as potential methods were proposed [13]. During 1990's, sampling-based motion planning methods, which are still actively studied, exhibited remarkable progress in their theory and applications[14, 3]. In 2000's, along the significant improvement in capacity of computers, the motion planning techniques, mainly

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sampling-based methods, has been utilized in various applications with many DOFs, such as trajectory planning of robots in production lines and medical and bioinformatic computations.

On the other hand, motion planning technology and humanoid robotics started being integrated in early 2000's [12] along with the rapid progress of sampling-based methods that has affinity with problems with many DOFs. At the same time, motion planning was used to generate the movement of animation characters in computer graphics[7]. The authors joined this exciting research field of humanoid motion planning, focusing on whole-body motion generation. Starting from two-stage methods where geometric and kinematic motion planning first provides the path of humanoid base that is converted into whole-body trajectory with dynamic motion pattern generator and inverse kinematics (IK) allowing task execution in workspace. As a result, we have demonstrated its feasibility through manipulation while walking [27] and pivoting manipulation of bulky objects [29] by full-size humanoid HRP-2. Optimization was also applied to dynamic whole-body motion and multi-contact motion generation [15]. A collection of advanced work on humanoid motion planning was published in 2010 [10].

Till then we concentrated on motion planning by regarding humanoid as just robots with many DOFs without really its characteristics of human-like shape. However, while planning and generating a variety of humanoid motions, we got interested in "natural" humanoid motions, which correspond to the motions human should make. Our first human-aware motion is walking path planning [18] that can generate paths including lateral motions when the goal is close and aside, not only the normal walking path whose velocity is in the front direction, modeled in the same way as non-holonomic motion for car-like robots. We also noticed that some multi-contact motions with dynamic constraints look human-like. These observations brought us to further investigation of human motion: is human optimizing something when they move? If yes, what are the optimization criteria? Although these are still not completely solved, we first tried to approach by analyzing and imitating the human motion and to see what we can get.

From 2013 we joined "METI Robotic Devices for Nursing Care Project" [22] that is a national project to support companies developing assistive devices that reduce burden of the elderly as well as caregivers using robotics technology. We addressed a challenging problem of using a humanoid robot as a subject that evaluates the devices by wearing assistive devices instead of human. We showed that this approach is useful because we can evaluate the supportive effects in a quantitative manner by measuring motor torques with and without the wearable device, whereas it is difficult to directly measure forces applied to human body [17]. We also enhanced the digital human that models surface shape, musculo-skeletal structure and interactions with humans and environments [30]. We continue addressing human motion understanding to better reproduce human motions with a humanoid robot.

Human-based humanoid motion planning is not only useful for evaluation of assistive products, but also designing motions of disaster response and heavy-duty robots. In case of disasters in artificial structure like nuclear plants, humanoid robot could be advantageous because it can easily access to environments made for human. In 2015 DARPA Robotics Challenge (DRC) [4] was held as a competition of capacity of doing tasks in the real world. One of the examples of heavy-duty task is assembly for airplane manufacturing. Human workers are often forced to do such tasks as cabling and device installation under very difficult posture. This is another typical field where humanoid robots can serve, as they have affinity to human workers' workspace and possibly execute tasks in their place to reduce their load. In both applications, human motions can offer many suggestions about how the humanoid adapt the environment and execute the tasks. If we can model human behaviors and interactions with products as motion primitives will help product design as we can test the digital mockup using the human model, without building hardware prototypes. We expect that those behaviors can be modeled as basic motion primitives that can be tuned and combined to reproduce higher-level complex behaviors. Human-based motion generation is also valuable for graphics animation, for instance crowd simulation and motions in games.

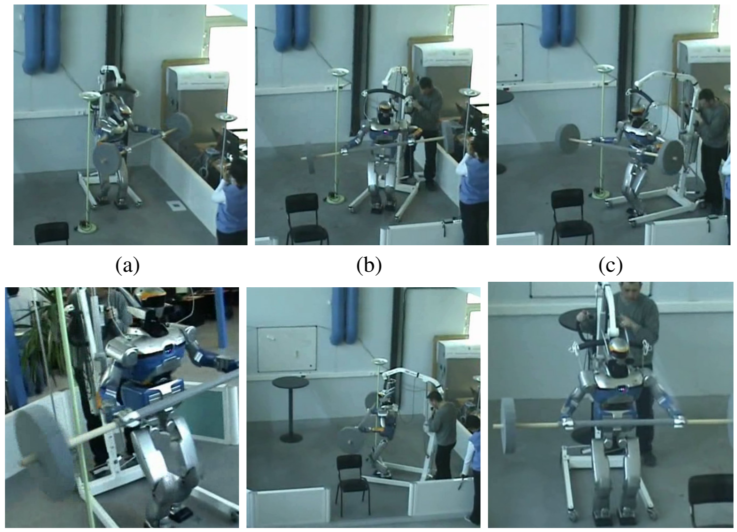
2 Humanoids meet planning

The early important work of humanoid motion planning was made by Kuffner et al. [12] where sampling-based motion planning was first applied to human-size humanoid robot. In the computer graphics field, motion planning techniques are used to deal with motions of digital characters as it is easier to generate motions of multi-DOF structure like [7].

2.1 Whole-body dynamic motion planning

We have proposed a two-stage method [27] that plans the path of robot base at pelvis in the first stage using a well-established method [24] for car-like robot, by taking into account the feature of walking that it is always easy to move in the direction that robot is facing. Then in the second stage the planned path is transformed into 3D dynamically stable walking motion based on Zero Moment Point (ZMP) [11] while ensuring the upper body does not collide with obstacles during manipulation of a long bar Figure 1 shows the obtained experimental results.

In the above work we dealt with the walking and upper-body separately, which means the walking motion was planned first and then the apply adjustments by shifting pelvis position to absorb the "disturbance" caused by the upper-body motion for maintain stability. We came to a question about whether we can generate a motion incorporating the upper and lower body at the same time. The approach taken here was to integrate the walking pattern generator into the priority-based generalized IK [23]. We have taken advantage that the ZMP-based walking pattern generator using



(a) (b) (c)

(d) (e) (f)

Fig. 1 Experiment of 3D collision-free motion for bar-carrying task

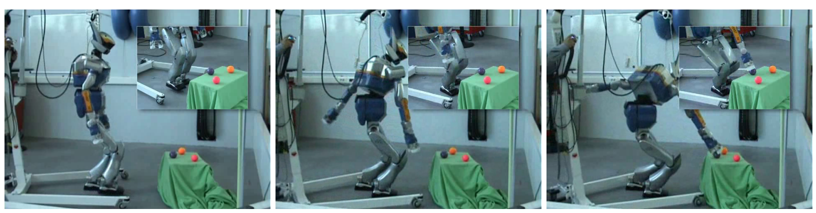


Fig. 2 Whole-body reaching motion integrating upper-body motion and stepping.

preview control [11] outputs the velocity of Center of Mass (CoM) for dynamically stable walking motion for specified footsteps. The desired CoM velocity can be easily integrated in the task-priority generalized IK to generate stable whole-body motions smoothly combining those of arms and legs as shown in Fig. 2 [28]. Although no particular tasks were assigned to the upper-body, some people remarked that the resultant motion was human-like: bringing the other arm backward as the consequence of IK that is a local optimization keeping the CoM around the center of the support polygon. From this period we start being interested in human-like motions.

2.2 Multi-contact dynamic motion

Human daily activities include many motions with multiple contacts with environments and objects, not only walking. Therefore, collisions or contacts should not be just avoided but exploited to achieve complex tasks. Multi-contact humanoid motion planning was pioneered by Kheddar, Escande et al. since mid-2000's, and this is still a very active research field. Multi-contact motion planning and generation is challenging in several aspects: it requires coordinated whole-body motion, flat-plane stability criteria like ZMP is not valid any more, and contact space between the robot and the environments is volume zero for planning.

After developing multi-contact motion planning methods [6, 2], we have investigated dynamic motion generation through optimization [15]. We have modeled the problem of optimal trajectory generation as a Semi Infinite Programming (SIP) by parameterizing the joint trajectories with uniform cubic B-Splines curves. The motion is decomposed into several contact phases and we formulate the multi-contact motion generation as an optimization problem that minimizes the following cost function C, under the constraints of mechanical limitation of the robot and multi-contact stability.

As the objective function, we consider a weighted sum of the motion duration, square torques and jerks as follows:

$$C_r(q_r) = \sum_{i=1}^{N_p} aT_i + \sum_{i=1}^{N_{dof}} \int_0^T \left(b\Gamma_i^2 + c\dddot{q}_{r,i}^{\,2} \right) dt \tag{1}$$

where T_i is the time duration of phase i and N_p the number of phases ($T = \sum_i^{N_p} T_i$) in the first term. In the second term, N_{dof} denotes the number of DOF, Γ_i and $q_{r,i}$ are the torque and joint angle of i-th joint of the robot. Optimization is performed by taking into account constraints

$$g(q_r) \leq 0 \tag{2}$$

including equalities and inequalities that correspond to constraints such as robot dynamics, contact conditions and stabilities, where the vector q_r and Γ denote joint angles and torques for whole robot. These constraints are considered when the optimization is solved by solvers like IPOPT [26]. It is always not easy to determine the weights, and here we set $a = 5$, $b = 1e^{-2}$, $c = 1e^{-6}$ that are empirically determined through several simulations. Recently, "inverse optimal control problem" is intensively studied to systematically compute those weights [19], which could help determining the composition of objective functions.

Figure 3 shows a typical multi-contact dynamic motion that supports the body by putting on a hand to reach a position under the desk. By introducing the time duration and dynamic multi-contact constraints for global trajectory optimization, we could obtain natural-looking smooth motion that could not be possible with only static or planar stability constraints.

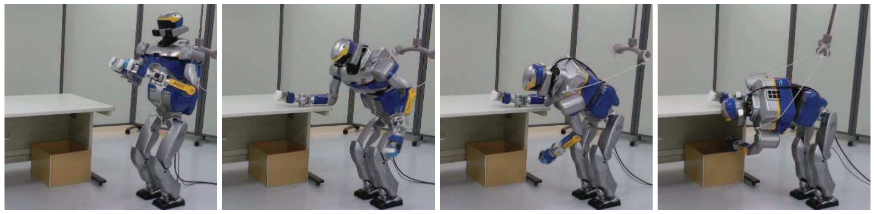


Fig. 3 With the right arm, the HRP-2 robot takes an additional support on the desk, which allows it to stably lean and put a ball into the box located under the desk.

3 Reproducing human motion by humanoid using optimization

The motion planning and generation methods with local and global optimization presented in Section 2.1 did not explicitly imitate human motions although they often produce motions that are natural-looking and human-like motion. These results suggest that humans may optimize some of criteria that we have introduced previously. In this section, we introduce some research on human-like humanoid motion generation based on optimization.

3.1 Human motion reproduction through optimization

An alternative direct approach for human-like humanoid motion generation is a process called "retargeting" that converts human motions, often measured as marker positions by motion capture systems, into motions of digital actors and humanoids [9, 21, 16]. Retargeting has been intensively studied envisaging such applications as not only natural human-robot interfaces and entertainment use, but also evaluation of assistive devises by using a humanoid as an active dummy [17]. In the last application, we can exploit the anthropomorphic shape and structure of humanoids by making it use or wear the assistive devices to provide quantitative evaluation by measuring joint torques, which is difficult with humans.

A standard way of retargeting is a sequential processing. The marker positions are first converted into joint angles, and then the motion is adjusted in order to meet the mechanical constraints such as joint limits and stability conditions. Although closeness to the original human motions can be used as an objective function of optimization of the first step, modification of trajectory in the second step may induce inconsistency with respect to the original human motions.

In order to overcome those issues, we have introduced a simultaneous optimization for criteria for both robots and humans [1]. In this optimization, we optimize not only the objective function $C_r(q_r)$ in eq. (1)for the robot, but also a combined one:

$$\min_{q_r, q_h, \phi} \quad C_{r,h}(q_r, q_h, p_h^{ref}, \phi)$$
$$\text{s.t.} \qquad g(q_r) \leq 0$$
$$h(q_r, q_h, \phi) = 0$$

where q_h, p_h^{ref} and ϕ are joint angle of the human model, marker positions, and human geometric parameters respectively. Some part of q_r and q_h are "shared" by the robot and the human to ensure the motion compatibility. The geometric parameters ϕ mainly represents the body link length to absorb the geometric difference between the robot and the human. Here the equality constraint $h(q_r, q_h, \phi) = 0$ implies how to map the coordinate of each body segments between the robot and the human. The constraints $g(q_r) \leq 0$ can be taken into account during the optimization in the same manner as in Section 2.

This method allows generating robot motions as close as original human motion within a unified framework of simultaneous optimization, while keeping track of how the features of human motion, such as joint trajectory, the dynamics of CoM and ZMP, are preserved or modified as a result of retargeting. Since the human motion q_h is also included in the optimization, the resulting motion can be regarded as the motion the human would make if he had the same constraints as the robot. We can take advantage of this property of this method by estimating what kind of human motions can be reproduced by the robot. The method is illustrated in Fig. 4 [1].

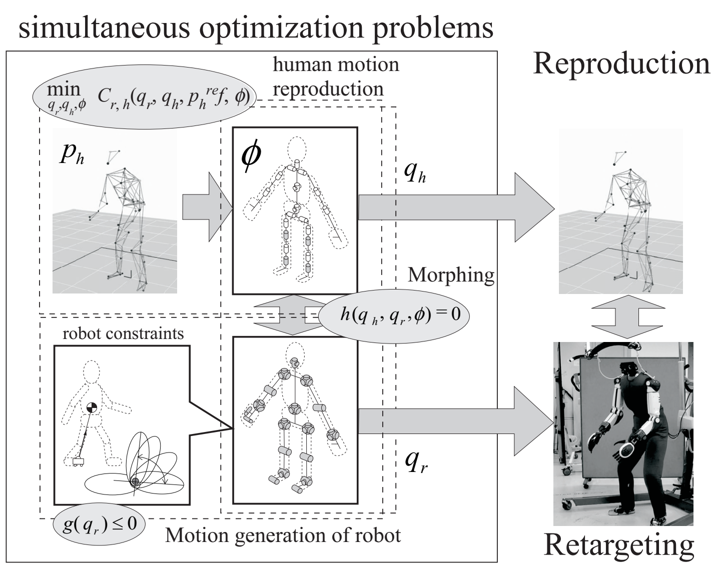


Fig. 4 The framework of human motion retargeting based on simultaneous optimization for the human and the robot.

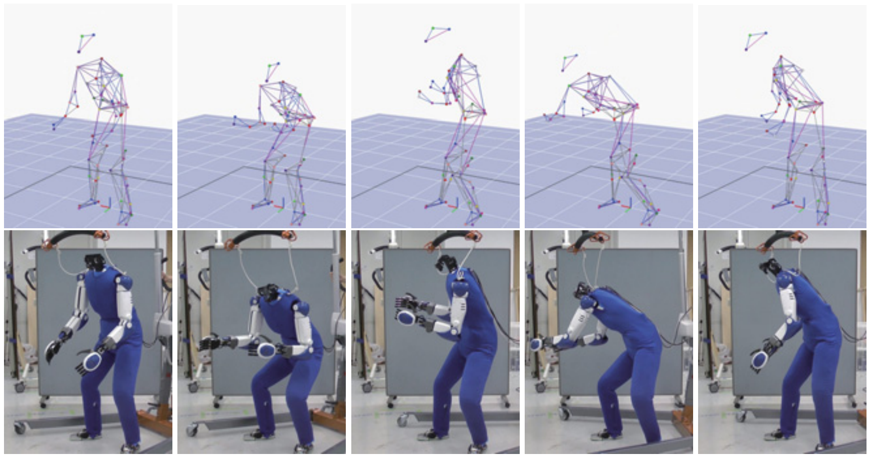


Fig. 5 Snapshots of a retargeted assisting motion. The upper row shows the markers and skeleton captured human motion. The retargeted humanoid motion with HRP-4 is shown in the lower row.

As mentioned later, we can use this method as a part of human-in-the-loop planning to utilize human motion as the basic path for complex humanoid motion in constrained environments. Figure 5 shows the snapshot of a captured caregiving motion by the humanoid robot HRP-4. We can observe that the humanoid robot reproduces whole-body motion by maintaining its stability although the motion speed was reduced by three times due to its mechanical limitation.

3.2 Constraints shape motions

The resultant motions from optimization depend not only on its objective function but also constraints. Together with the objective function that is supposed to govern human motions, we expect that constraints also “shape” the generated motions. For instance, in applications of assistive device evaluation by a humanoid robot, it may be necessary to reproduce some constrained motions of the elderly or the handicapped. As it is difficult to test or evaluate the device by the subjects with the disability, humanoids can be helpful if they can replace those specific subjects using the device.

We have verified this possibility by some basic experiments in our previous work [15] based on the framework of optimization in 2.2. Figure 6 shows the results of walking motions generated based on the optimization in eq. (1) by providing the contact sequence of footsteps. Although it is not still a natural walking motion, we regard this as the basic walking motion without any constraints.

In order to see the difference of motions with additional constraints, we introduced a desired upper limit of the contact force of the (left) foot. The observed average ground reaction force is 590N during standby standing posture and even larger during walking. We here added an inequality constraint limiting the contact force of the left foot less than 500N during the walking motion. The resultant robot motion is shown in Fig. 7. When we have a sore foot, we try to minimize the force on the foot by leaning on the other foot. In this experiment, we can see similar behavior with the right knee more deeply bent than the left one. Figure 8 shows the vertical force measured by the force-torque sensors at the ankles. Except the peak due to the error of open-loop trajectory control, the force at the left foot is maintained around 500N. It is also noteworthy that a preparation phase appears before the left foot stance phase (during the double support phase) used to accumulate kinetic energy.

In this section, we demonstrated that the optimization process can possibly reproduce human motions with humanoid robots. Inverse optimal control is one of the promising methods to model human motions to investigate on what criteria humans adapt or optimize their motions. We also showed that human motions with disability can be reproduced by identifying the corresponding constraints and applying to the optimization process. This method will open a new perspective of simulations and humanoid imitation of disabled motions.

4 Toward human planning

We have tried to analyze and understand human motions through their reproduction by humanoid robots. Those findings can also be beneficial to predict, or to plan

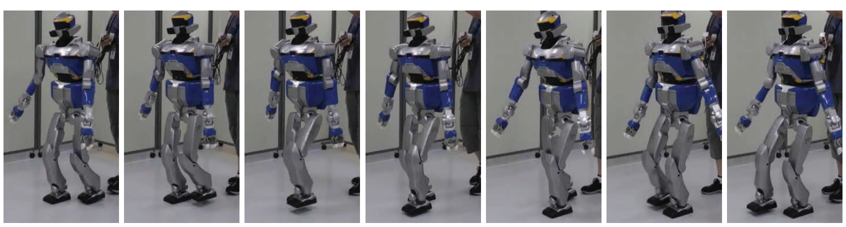


Fig. 6 Walking motion generated from multi-contact optimization.

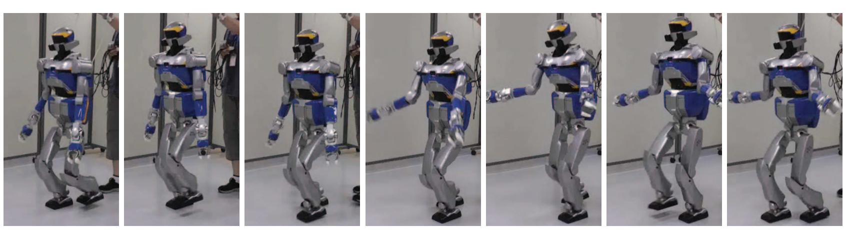


Fig. 7 Walking motion generated with constraints of sore foot.

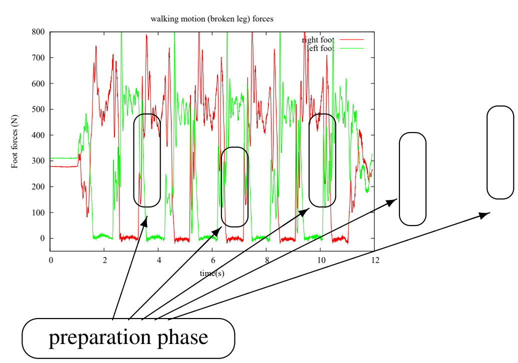


Fig. 8 Foot forces during the broken leg walking. The double support phase is used to accumulate kinetic energy to cope the broken leg.

human motions including interactions with environments and devices using a more detailed body model.

In this section, we introduce some of ongoing research and future perspective toward “human planning”.

4.1 Reproducing interactive human motions

When we design a device for human, especially an assistive device, it is important to know the physical interactions between the device and a human. If a simulator can reproduce human behaviors precisely, it allows estimating the positive and negative effects of the device without making hardware prototypes that is time-consuming.

The design cycle time can be reduced by performing several design refinements with a simulated human and the device before making a semi-final product prototype.

In “METI Robotic Devices for Nursing Care Project” [22], the AIST is working in the consortium of device standardization and evaluation, and has been developing a “digital human model” including skin surface and interaction modeling, physical simulation with joint torques, and musculo-skeletal structure.

As the first step of device evaluation with simulation, we have developed the skin deformation and interaction model [30]. The simulation consists in modeling skin deformation of a human body and physical simulation coming from interaction with the assistive device for transfer.

The skin deformation is computed by linear blend skinning (skinning in short) that is integrated into a rigid-body articulated dynamics model. Here, the surface of the human body and the device are both approximated by triangle meshes. The interaction force applied to the human from the device is computed at the contact points of both surfaces. The component of the device supporting the human is modeled as a rigid body or mass-spring model. The contact force f is then transformed into joint torques τ by inverse mapping based on the skinning equation that relates joint angles with skin vertices by:

$$\tau = J^T f \tag{3}$$

where J is the Jacobian representing the relationship between contact point and the joint angle.

Figure 9 shows an example of simulation of a robotic lift device used to hold the subject to be transferred between different places. When the supporting part is horizontal, the body fell from the support. In contrast, the successful result was generated with the inclined (7 degrees) support. Although the human active motion is not yet simulated, this result shows possibility of “human motion planning” evaluating the supportive effect for design improvement of such devices.

4.2 Human-in-the-loop planning

As mentioned earlier, the motion planning technique, represented by sampling-based methods, has made tremendous progress as a powerful tool. Nevertheless, it is still a challenging problem to plan a natural motion of human figures or humanoids that require consideration of many mechanical constraints and dynamics stability, as well as measured human motions to reproduce. Recently, a planning scheme called “human-in-the-loop planning” is drawing attention in the planning field. Especially for narrow passage problems and motions involving contacts, the planning efficiency is drastically improved by using an initial path planned by the human with some interfaces with intuitive control [5, 25].

We consider this observation also applies to humanoid motion planning for complex tasks. In DARPA Robotics Challenge (DRC) [4], several manipulation tasks are

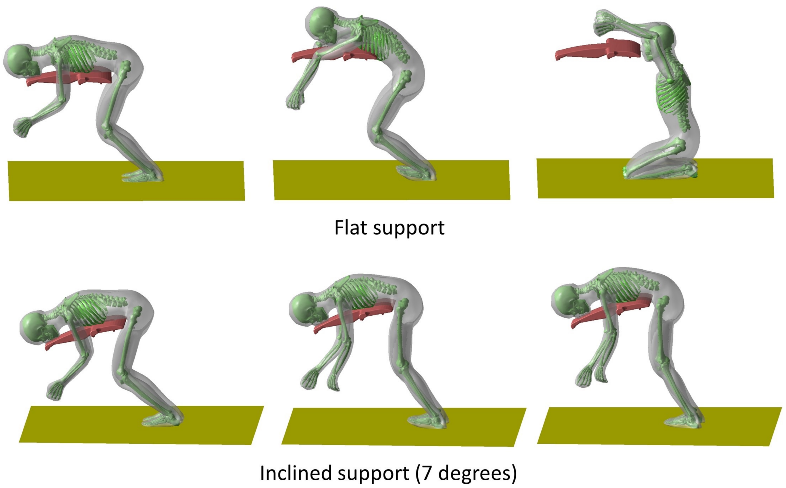


Fig. 9 Simulations of behavior of a human supported by a robotic lift device. In the upper images, the human cannot be lifted with a flat support part. The successful lift with inclined support is shown in the lower images.

required such as door opening, turning valves, making a hole on the wall with tools, pushing a button and plugging a socket. The difficulty lies in the variance of tasks whose parameters like the valve diameter or manipulation positions are changed over time. The robot should perform measurements in the world to localize and to recognize the target objects.

In this competition, the robots are basically teleoperated with certain autonomy in such a way that the robot generates necessary reaching or manipulating motions by providing the target object from a graphical user interface (GUI) based on Choreonoid humanoid simulation framework [20] as shown in Fig. 10. However, some of the teams encounter difficulties in generating coordinated whole-body motions due to kinematic singularities or constrained environments. This problem can be dealt with by testing several end-effector orientations or giving many intermediate waypoints, but this severely slows down task execution because of limited bandwidth to get information from the environment. In addition, even advanced motion planning or optimization methods need long computation time to derive a solution path due to the complexity of the problem.

The retargeting scheme presented in 3.1 could be useful to solve the above problems. This retargeting framework can backproject the retargeted robot motions into human motions, which means that it can generate human motions as if the human had the physical or mechanical constraints of the robot. By integrating an immersive tele-presence device with virtual reality and physical feedbacks like TELESAR [8], the human operator can feel“embodiment” into robots in order to input the robot motion by considering its constraints.

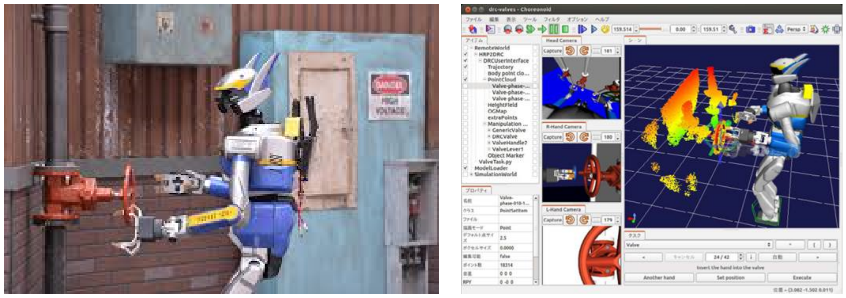


Fig. 10 HRP-2 humanoid robot of AIST-NEDO team executing the valve turning task, and its teleoperation GUI on Choreonoid during DARPA Robotics Challenge.

We may use these motions from human under robot constraints as the initial path of motion planning, as well as motion primitives of the task that can be parameterized to adapt to task variations. By taking advantage of human intuition as an initial guess, the efficiency of motion planning could be much more improved than starting planning from stratch. Figure 11 illustrates this human-in-the-loop motion planning combined with immersive interface.

5 Summary

This paper discussed new perspectives in the motion planning related to humans and humanoid robots. At the early research stage our primary interest was how to generate humanoid motions that exploit many DOFs including arms and legs. Intensive study on whole-body humanoid motion planning and optimization, including multiple contacts, brought us to interest in human-like motion. Driven by projects including evaluation of assistive devices using a humanoid robot as a subject, we have developed a motion retargeting method based on simultaneous optimization for human and humanoid motions.

Finally, some current work is introduced: "planning humans" and "human-in-the-loop" planning. As an important factor of simulation-based assistive device evaluation, we have also developed a simulator that reproduces human behaviors when interacting with those devices. Here, upcoming challenges include usage of inverse optimal control to investigate what the humans optimize during their motion. Another challenge is application of motion retargeting to human-in-the-loop planning, inspired by DRC where complex humanoid motion planning should be done efficiently. Together with an immersive interface, the human operator is expected to input motions as if he/she had the robot constraints, which can be used the initial path for complex motion planning and motion primitives for adaptive task execution.

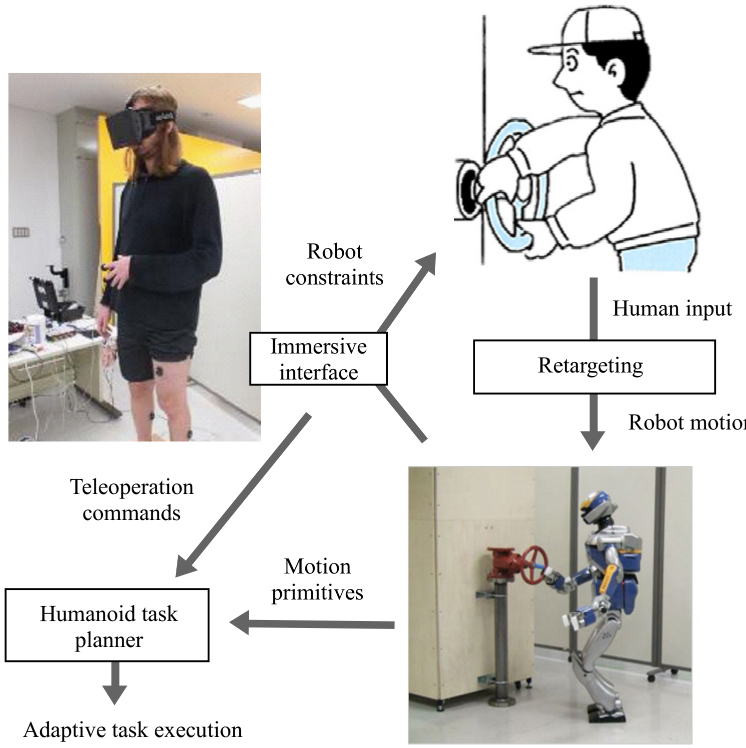


Fig. 11 A future framework of human-in-the-loop planning that allows human to generate motions under robot constraints. The resultant motions can be used as motion primitives for adaptive task execution.

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