# Natural trajectory generation for Robot-Human cooperation for sit-to-stand assistance

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*Abstract*— **This paper presents a method to determine trajectory for robot that involves a close interaction between robotic systems and human beings.The proposed method considers robot trajectory as path in operational space and time rhythm distinct problems verifying the natural smoothness of voluntary human movement. Operational space path is determined experimentally as individual movement pattern. The human voluntary movement smoothness is quantified by a function: the jerk. Than, minimizing the time derivation curvilinear abscissa acceleration, we found the function of the time that defines the time rhythm along the trajectory. This method is applied on a robotic device like "walking aid" developed in LRP to provide support during the walk and sit to stand transfer. During the verticalisation, the robot handles have to help the user to sit-to-stand more naturally as possible.**

*Keywords*— **Assistive device, sit-to-stand transfer, minimum jerk, trajectory generation**

## I. Introduction

WAL king is often the primary form of exercise for the elderly. Since inactivity contributes to increased morbidity and mortality in older adults, devices that facilitate mobility and daily exercise may promote improved health and well-being. Ambulatory assistive devices such as canes and walkers offer stability and provide means whereby many frail older adults could maintain mobility, functional independence and social interactions. The stability from the assistive devices is directly proportional to the energy needing to be expended by the user; this is a serious challenge to frail and elderly persons.

Fig. 1. Guido, Marc, Care-o-bot, Pearl, Walkabout

In addition, there would therefore be a very high manpower demand on the healthcare professionals in a nursing home to maintain a reasonable mobility for the needed residents. It is therefore not surprising to observe, in the nursing area, that many frail nursing home residents are immobilized unnecessarily, resulting in significant morbidity and mortality, many of which are potentially preventable. Active devices for postural compensation can free medical staff for other tasks, and help patients to do rehabilitation exercises with various difficulty levels.

Some robotic systems have been developed to provide active assistance during walking, in particular Guido [3], Marc [4], Care-o-bot [5], NurseBot Pearl [6] or Walkabout [7]. Most of those systems have been designed to give a light support and be used more like a stability aid. Their main feature is in navigation, as finding paths that are obstacle free or giving information about directions. They have not been designed to allow walking rehabilitation such as Where [8] or Hitachi walker [9], in Figure 2.

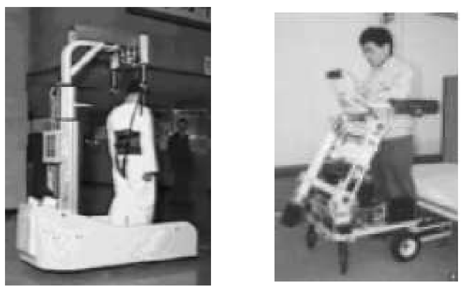

Fig. 2. Where, Hitachi walker

As to MONIMAD system (Figure 3), it has been specially designed for mobility rehabilitation assistance and allows assisted transfers from walking to standing positions [12].

The handles pull first the elderly patient in an antepulsion configuration: two degrees of freedom are needed to keep handles horizontally. This is done using two parallel mechanisms mounted on top of each other (passive four bars linkage and Scott-Russel mechanism [21]). In addition, the handles are independent in order to restore balance when the user begin to lose it.

To lift softly frail elderly person, the Handle Robot Trajectory has to be as natural as possible. This assistive device has two main functions:

- Postural stability, to provide support and avoid fall during the walk.

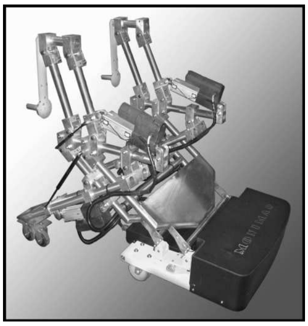

Fig. 3. MONIMAD Prototype

• Verticalisation, to help elderly during stand-up and sit-down transitions.

The designed robotic system is a two degrees of freedom mechanism mounted on an active mobile plateform (see Figure 4). For the sit to stand transfer, the Robot

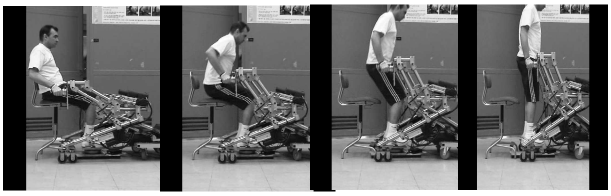

Fig. 4. Guided arm movement during assisted sit-to-stand transfer

handles first pull slowly the patient to an antepulsion configuration. Then, the handles go from this down position to the up position, which is the position used for walking. Obviously, the handles must remain horizontal during the whole transition. This is obtained using two parallel and independent mechanisms combined in a serial way. Details on the design of this assistive device can be found in [12].
To lift softly frail elderly person, the Handle Robot Trajectory has to be as natural as possible.
In recent years new human-robot interfaces based on direct interaction through a contact have been investigated through the arm-manipulator coordination for the problem of load sharing. For this kind of cooperative motion control, human characteristics are approximated by an impedance model [1] or a variable compliance control [2], in which the robot plays a passive role. Unlike that, the assistance of sit-to-stand refers to sharing guidance along a trajectory as natural as possible to move frail persons.

## II. Problem

The term "trajectory" refers here to Cartesian-space planning of the robot handle movement. "Natural Trajectory" are requested for comfortable human movement assisted by robotic devices. From our point of view, "Natural" is relevant to :
• trajectory path compatible with hand movement when the sit-to-stand transfer is assisted by someone else,
• smooth and continuous motion of the hand.
As proposed in [10], smoothness can be quantified as a function of jerk, which is the time derivative of acceleration. From this point of view, to move something from location $X_i$ to $X_f$ in $T$ seconds, the minimum jerk trajectory would be expressed by the function:

$$X(t) = X_i + (X_f - X_i)(10(\frac{t}{T})^3 - 15(\frac{t}{T})^4 + 6(\frac{t}{T})^6) \quad (1)$$

Trajectory planning based on minimizing the jerk is used to obtain smothness simple movement in Robot-Human arm collaboration [14], [15], [16]. While complex hand trajectories are view as composed of partially overlapping linear strokes (modeled as B splines with bell-shaped speed profiles) in [17]. The parameters of the model (timing scale, and position of each segment) were initially extracted from the experimental data and then adjusted iteratively until a good fit to the observed trajectories was obtained.
But, in our trajectory characterization control points location and occurrence are unknown, this method has to be modified.
However, experimental data are needed to implement the trajectory generation for the handles of our prototype.
For each patient, several sit-to-stand transfer trajectories was recorded [12] and some examples of these trajectories are given Figure 5. Analysis of the transfer

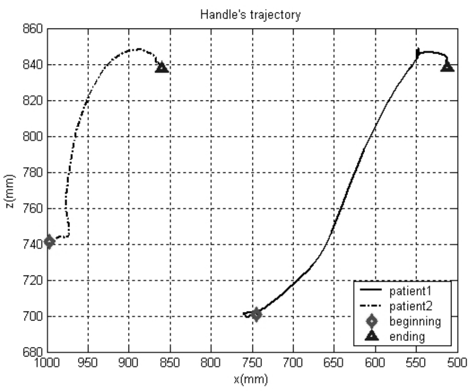


Fig. 5. Experimental sit-to-stand transfer trajectories

trajectories records show some interesting points:
• The sit-to-stand transfer trajectory follows a curve such as those normal deviations on both sides of the straight line between the two end points never exceed 15% of the total trajectory length for all the patients.
• The global shape of the trajectory looks like a "s-curve" and is not directly related to the age or height of the patient but seems to be correlated with its own personal strategy to stand up or sit-down.
These items can't be considered as rules (since the number of patients is not statistically significant and since the observed trajectories are the result of an interaction between the caregivers and the patient) but rather like practical guidelines for the trajectory generation described in the next section.

## III. Method

The Robot Handles Trajectory (RHT) has to be similar to the general curve in Figure 6.

The main idea presented in this paper is to decompose the trajectory characteristics into a physiological part and a mechanical part.

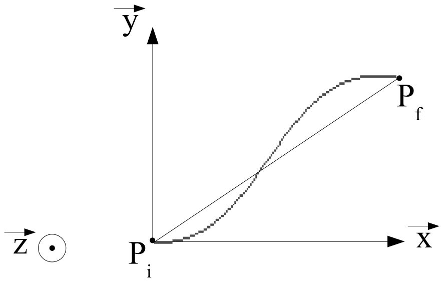


Fig. 6. The Robot Handle Trajectory (RHT) in Cartesian-space

Minimum jerk is a physiological constraint for smoothness and infers only in trajectory quality. Thus, natural coordinate is used to describe the trajectory function verifying minimum jerk.

Geometrical path describing hand or some other end effector trajectories are not time dependent and may be expressed in term of Euclidean coordinates.

At last, the trajectory is a time function of Cartesian coordinates generating a smooth movement.

### A. Natural parameter

Let $s(t)$ represents the distance which the Robot Handles have moved along the curve at instant t. $s(t)$ is called the natural parameter of the curve $\gamma$ representing the trajectory. The natural parameter $s(t)$ crosses the image of $\gamma$ at unit speed so that [19]: This allows to define Frenet vectors and to relay natural parameter and Euclidean position. Let : $\vec{r}(t)$ represents the instantaneous position vector of the robot handles. Then the tangent unit vector $\vec{T}$ is defined as [20]:

$$\vec{T} = \frac{d\vec{r}}{ds}$$

That yields the relation used to define the Robots Handles Trajectory in spatiotemporal space:

$$\left\| \frac{d\vec{r}}{ds} \right\| = 1 \tag{2}$$

The natural parameter is entirely defined by the smoothness characteristic of the robot handles trajectory. By applying relation (1) to $s(t)$ we obtain:

$$s(t) = s(T_i) + (s(T_f) - s(T_i))(10(\frac{t}{T_f - T_i})^3 - 15(\frac{t}{T_f - T_i})^4 + 6(\frac{t}{T_f - T_i})^5) \tag{3}$$

### B. Robot Handle's Path in Euclidean vectorial space

Examining the global shape of the experimental curves presented in previous section and in conclusion of trajectory characterization, it is observed that an assisted sit-to-stand transfert follows a path similar to the one shown in Figure 7.

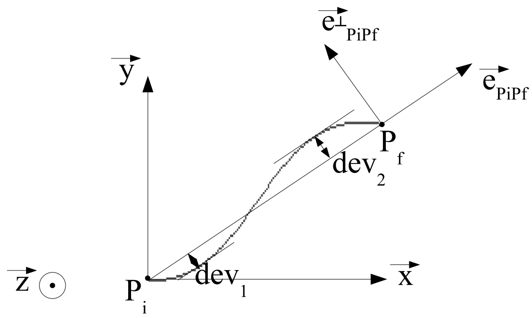


Fig. 7. Hand's path during an ssisted sit-to-stand transfer

This kind of curve will be defined by a third order ploynom in the $(P_i, \vec{e}_{P_iP_f}, \vec{e}^{\perp}_{P_iP_f})$ plane, with : $\vec{e}^{\perp}_{P_iP_f} = \vec{z} \wedge \vec{e}_{P_iP_f}$. Considering point $P$ on the HRP curve : $\vec{P_iP} = X\vec{e}_{P_iP_f} + Y\vec{e}^{\perp}_{P_iP_f}$, its plane coordinates verify : $Y = \sum_{i=0}^{3} \alpha_i X^i$ and the path constrains gives us the RHP equations:

$$\begin{aligned}
&\alpha_0 = 0\\
&\alpha_1 X_1 + \alpha_2 X_1^2 + \alpha_3 X_1^3 = Y_1 \ (= dev_1) \quad (A)\\
&\alpha_1 X_2 + \alpha_2 X_2^2 + \alpha_3 X_2^3 = 0 \quad (B)\\
&\alpha_1 X_3 + \alpha_2 X_3^2 + \alpha_3 X_3^3 = Y_3 \ (= dev_2) \quad (C)\\
&\alpha_1 X_4 + \alpha_2 X_4^2 + \alpha_3 X_4^3 = 0 \ (where\ X_4 = \overline{P_iP_f})\\
&\left(\frac{dY}{dX}\right)_{X_1} = \alpha_1 + 2\alpha_2 X_1 + 3\alpha_3 X_1^2 = 0\\
&\left(\frac{dY}{dX}\right)_{X_3} = \alpha_1 + 2\alpha_2 X_3 + 3\alpha_3 X_3^2 = 0
\end{aligned}$$

Solving first the $(A), (B), (C)$ linear system, coefficients $\alpha_i$ are expressed in term of $X_1, X_2, X_3$:

$$\begin{aligned}
&\alpha_1 = (X_2(X_1^3 Y_3 - Y_3 X_2 X_1^2 - X_3^3 Y_1 + X_3^2 Y_1 X_2))/\Delta\\
&\alpha_2 = -(X_1^3 Y_3 - Y_3 X_2^2 X_1 - X_3^3 Y_1 + X_3 Y_1 X_2^2)/\Delta\\
&\alpha_3 = (X_1^2 Y_3 - Y_3 X_2 X_1 - X_3^2 Y_1 + X_3 Y_1 X_2)/\Delta\\
&\text{where } \Delta = X_1 X_3 (X_1 - X_2)(X_1 - X_3)(X_2 - X_3)
\end{aligned}$$

Noting that $\Delta \neq 0$ for a RHP verifying:
$X_0 < X_1 < X_2 < X_3 < X_4$.
$X_1, X_2, X_3$ values are the solutions of the optimisation problem:

$$\begin{aligned}
min(f(X))\\
under\\
-X_1 < 0\\
X_1 - X_2 < 0\\
X_2 - X_3 < 0\\
X_3 - X_4 < 0
\end{aligned}$$

with: $f(X) = (\alpha_1 X_4 + \alpha_2 X_4^2 + \alpha_3 X_4^3)^2 + (\alpha_1 + 2\alpha_2 X_1 + 3\alpha_3 X_1^2)^2 + (\alpha_1 + 2\alpha_2 X_3 + 3\alpha_3 X_3^2)^2$.

We observe that an acceptable solution would be such as: $|X_i - X_j| < 2\%$ length curve. This solution gives the polynom coefficients with respect to the morpho-pathological parameters of the user. Moreover, individual HRP is totally defined at this point.

### C. Robots Handles Trajectory in Spatiotemporal space

The Robots Handles Trajectory in spatiotemporal space is defined by $X$ and $Y$ coordinates as time functions, such as $r(\vec{t}) = X(t)\vec{e}_{P_iP_f} + Y(t)\vec{e}^{\perp}_{P_iP_f}$. Then relation (2) yields the condition:

$$(\frac{dX}{ds})^2 + (\frac{d}{ds}(\sum_{i=1}^{3}\alpha_i X^i))^2 = 1$$

Using the derivative operator linear property, previous relation becomes:

$$(1 + (\sum_{i=1}^{3} i\alpha_i X^{i-1})^2)(\frac{dX}{dt})^2 = (\frac{ds}{dt})^2$$

Where $\frac{ds}{dt} \succ 0$, then, determination of the time function $X(t)$ is obtained integrating the equation :

$$\sqrt{(1 + (\sum_{i=1}^{3} i\alpha_i X^{i-1})^2)}(\frac{dX}{dt}) = \frac{4\dot{s}_M}{T_f^2}t(T_f - t)$$

we replace the derivative $\frac{dX}{dt}$ by the finite difference approximation and we compute the estimate $P$ coordinates by the following recursive scheme:

$$\begin{cases} X(k+1) = \frac{(t(k+1)-t(k))(4\dot{s}_M t(k)(T_f - t(k)))}{(T_f^2\sqrt{1+(\sum_{i=1}^{3} i\alpha_i X(k)^{i-1})^2})} + X(k) \\ \\ Y(k+1) = \sum_{i=1}^{3}\alpha_i X(k+1)^i \end{cases} \quad (4)$$

Where $\dot{s}_M$ is obtained by calculating the RHP length using simultaneously the natural coordinate and the Euclidean coordinates:

$$\dot{s}_M = \frac{3(\sum_{i=0}^{N}\sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2})}{2T_f} \quad (5)$$

## IV. Results

In this section, experimental data is applied to the trajectory generator presented in previous section and the computed trajectory is compared to the experimental one.
The following Figure 8 shows an elderly hand path during an assisted sit-to-stand transfer.
In order to generate an individual Robot Handles Trajectory, some parameters are extracted from this curve:
- Initial point, $P_i = (484mm, 508mm)$.
- Final point, $P_f = (584mm, 610mm)$.
- Sit-to-stand time duration, $T_f = 2s$.
- Path length, $L = 143mm$.
- Deviation parameters $dev_1 = -0,3L = -4,3mm$ and $dev_2 = 0,1L = 14,3mm$.

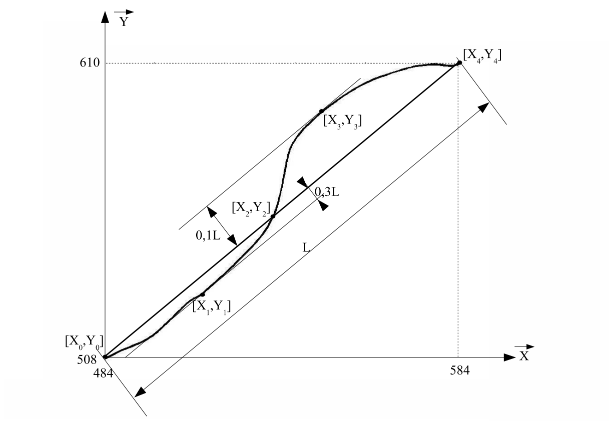


Fig. 8. Patient trajectory

### A. Bio-mimetic trajectory generation based on elderly data

The RHP in the $(P_i, \vec{e}_{P_iP_f}, \vec{e}^{\perp}_{P_iP_f})$ plane is first defined by searching coefficients of a third order plolynom passing from five points:

| | |
|---|---|
| $X_0 = 0mm$ | $Y_0 = 0mm$ |
| $X_1 unknown$ | $Y_1 = -4,3mm$ |
| $X_2 unknown$ | $Y_2 = 0$ |
| $X_3 unknown$ | $Y_3 = 14,3mm$ |
| $X_4 = 143mm$ | $Y_4 = 0mm$ |

Using MATLAB optimisation function "$fmincon$", an acceptable solution is found:
$[\alpha_1 = -0.57184 \ ; \ \alpha_2 = 0.014756 \ ; \ \alpha_3 = -7.528e - 005]$.
This result allows to define the searching polynom (Figure 9).

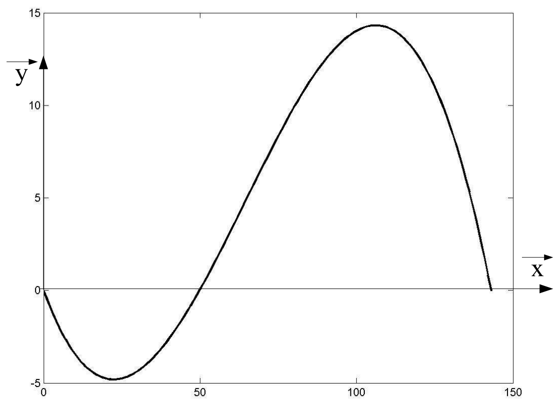


Fig. 9. Polynomial path

Along this path, the derivative of natural coordinate is bell shaped (Figure 10).

Numerical integration, using scheme (4), makes possible to obtain the Robot Handle Trajectory (RHT) in the $(P_B, \vec{e}_{P_BP_H}, \vec{e}^{\perp}_{P_BP_H})$ plane (Figure 11).

Finally, the trajectory is plotted in the reference frame

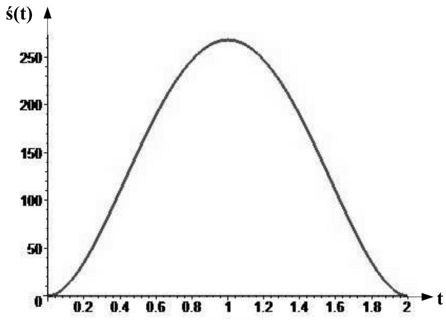


Fig. 10. Evolution of derived from curve's natural coordinate

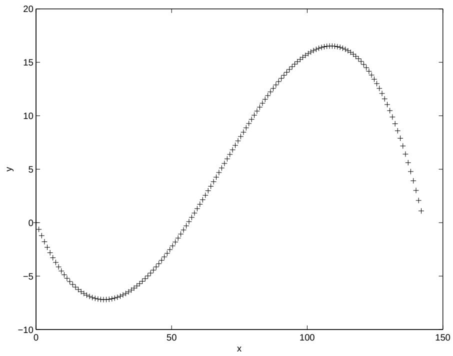


Fig. 11. Robot Handle Trajectory in the $(P_B, \vec{e}_{P_B P_H}, \vec{e}^{\perp}_{P_B P_H})$ plane

of the assisted device (Figure 12).

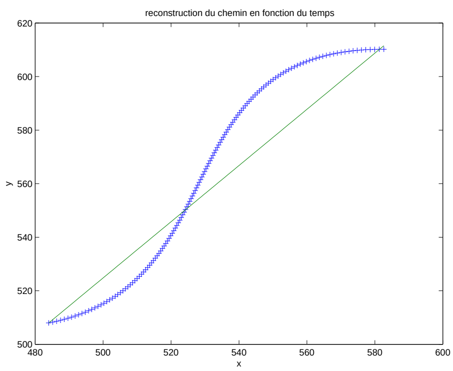


Fig. 12. Robot Handle Bio-mimetic Trajectory

This curve has the general characteristic of a measured elderly trajectory. The various models detailed in [13] will be used for the kinematical analysis and the robot control for assisted sit-to-stand transfer.
Figure 13 is the result of the implementation of the control of the robot for a patient during a sit-to-stand verticalisation.
We note that the trajectory of the robot follows well the calculated trajectory. However, we notice some errors which we considered negligible, due to diferent noises on the robot.

Fig. 13. Application in Clinical area

In order to demonstrate the efficiency of the assistive device during sit-to-stand transfer, several experimental standing-up and sitting-down trials were executed with a set of 19 elderly patients in Charles-Foix Hospital under the supervision of gerontologists and physiotherapists. The patients are affected with different pathologies disturbing the transfer.
Due to their physical condition and age, the number of trials by a patient is usually limited to four. Finally, on the set of all patients, we observe that:

- patient who could stand-up without human assistance, can stand-up with the assistive device,
- patient who could not stand-up with human assistance, cannot stand-up with the assistive device,
- patient who could not stand-up without human assistance, can stand-up with the assistive device.

The last remark would tend to prove the usefulness of our device since it can help elderly patient to stand-up and sit-down without human assistance.

## V. Conclusion

A method to determine trajectory for robot that involves a close interaction between robotic systems and human beings has been proposed. Robot trajectory as path in operational space and time rhythm are split into distinct problems verifying the natural smoothness of voluntary human movement. Operational space path is determined experimentally as individual movement pattern. The human voluntary movement smoothness is quantified by a function: the jerk. Than, minimizing the time derivation curvilinear abscissa acceleration, we found the function of the time that defines the time rhythm along the trajectory. This method is applied on a robotic device like "walking aid" developed in LRP to provide support during the walk and sit-to-stand transfer. Experiments with this assistive device have been conducted on a set of the elderly patients and demonstrate its usefulness since it allows elderly patients to partly recover their mobility.
The next step of this work will be the implementation of a virtual compliance control coupled with human motion estimation in order to maintain the postural stability of the user.

DRAFT


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