Autonomous reaching and obstacle avoidance with the anthropomorphic arm of a robotic assistant using the attractor dynamics approach

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Abstract

To enable a robotic assistant to autonomously reach for and transport objects while avoiding obstacles we have generalized the attractor dynamics approach established for vehicles to trajectory formation in robot arms. This approach is able to deal with the time-varying environments that occur when a human operator moves in a shared workspace. Stable fixed-points (attractors) for the heading direction of the end-effector shift during movement and are being tracked by the system. This enables the attractor dynamics approach to avoid the spurious states that hamper potential field methods. Separating planning and control computationally, the approach is also simpler to implement. The stability properties of the movement plan make it possible to deal with fluctuating and imprecise sensory information. We implement this approach on a seven degree of freedom anthropomorphic arm reaching for objects on a working surface. We use an exact solution of the inverse kinematics, which enables us to steer the spatial position of the elbow clear of obstacles. The straight-line trajectories of the end-effector that emerge as long as the arm is far from obstacles make the movement goals of the robotic assistant predictable for the human operator, improving man-machine interaction.

1 Introduction

Robotic assistants are partially autonomous robot systems that support human operators, with whom they interact through various channels of communication. To work in natural environments shared with the human operator, robotic assistants need an array of sensor systems and powerful perceptual algorithms so that they may acquire enough information about the scene to interpret user commands and perform autonomously actions such as orienting toward objects, retrieving them, possibly manipulating them and handing them over to the human operator. The robotic assistant CORA [1], [2], for instance, uses an active stereo camera system, haptic sensors, force sensors, and speech recognition to achieve communication and autonomous action (Figure 1).

In robotic assistance, autonomous reaching, grasping, transporting, and handing over must take place under specific boundary conditions. The environment is always dynamic, because the human operator may work in the shared workspace. Dynamic conditions are not only relevant to obstacle avoidance, but also potentially to transport movements, such as when the robotic assistant is to hand over an object or to position an object on a part held by the human operator. It would be very limiting, if the human operator was required to hold the part perfectly still.

Because scene representations are so difficult to extract from sensory information when the environment is not specifically prepared for robot, the perceptual information available about objects that must be picked up or handled is typically imprecise, geometrically fuzzy, and variable in time. Among the more challenging aspects, for instance, is the tracking of spatial locations at which the human operator’s arm is positioned. Thus, another requirement arising for autonomous reaching is that it may work on the basis of imprecise and variable information about the environment.

There is a sizeable literature on the planning of arm trajectories (summarized by [3]), which includes sophisticated and exact approaches. These typically require detailed metric information about the scene and are static in nature, requiring replanning when the scene changes. The potential field method, originally developed by Khatib [4] (see also [5]), is probably the heuristic approach most adapted to dealing with dynamic environments as well as with imprecise information (see the recent work of Khatib’s group, e.g.
The potential field approach has important strengths, most notably the integration of planning and control. It is not simple to implement, however, and has a fundamental limitation, the occurrence of spurious solutions, which can only be overcome with considerable effort (see, e.g., [7] and [8]).

Since 1992, an alternative approach has been developed based on attractor dynamics [9], [10], [11]. Like in the potential field method, the movement trajectory evolves in time from a dynamical system. For the potential field method this evolution is generated by descending along the gradient of a potential until a minimum is reached. In the attractor dynamics approach the trajectory is generated while the system is in a stable stationary state, a fixed-point attractor. This is possible through judicious choice of the variables in terms of which the trajectory is generated. For vehicle path planning, for instance, a potential field method would use the Cartesian position of the vehicle in the plane while the attractor dynamics approach would use heading direction and driving velocity as variables (see [12] for a discussion of the issue of which kinds of variables to use). One can perfectly sit in a fixed-point attractor of heading direction and velocity and still drive around.

In the potential field approach, the target is fed in as a function that has a minimum at the target location, obstacles are fed in as functions that have maxima at obstacle locations. In the attractor dynamics approach, the target contributes an attractor force to the dynamics of heading direction that pulls into the direction in which the target is seen from the vehicle. Obstacles contribute forces that repel from the heading directions at which obstacles are seen. The vehicle moves in the direction at which the resulting attractor for heading direction balances these different forces (somewhat analogously to the determination of heading direction in [13]). As the vehicle moves, the bearings of targets and obstacles change, so that the resulting attractor shifts. In the presence of obstacles, therefore, a complex trajectory may result even as the system is sitting all the time in a fixed-point attractor. Because the mathematical analysis of attractors and their bifurcations is much more complete than the analysis of all possible transient solutions of a gradient descent, spurious states can be avoided in the attractor dynamics approach [10].

For vehicles, this approach has been proven to work efficiently with very low-level sensory information that is metrically imprecise and fluctuates [14], [15]. The stability of the fixed-point attractors makes that the planning approach contributes to the stabilization of the system. Moreover, because the system tracks a moving attractor anyway, there is no principle difference between dynamic and static environments. In a simulation study, a very limited generalization of the approach to controlling movement of an agent in three dimensions has been made by using the two-dimensional heading direction in a plane that may be shifted vertically [16].

In this paper we show, how the attractor dynamics approach can be used to control the motion of a robot arm. We use the end-effector heading direction in 3D and its velocity to generate end-effector trajectories, which are transformed into seven-dimensional joint space using an exact inverse kinematics. The approach is formulated for the behavioral situation of a robot arm that reaches for objects on a working surface, to which the robot arm is attached. Reaching for objects thus always involves approach from above and obstacles must be avoided while remaining above the working surface. By choosing a kinematic solution of the redundant arm in which the “elbow” is high, the risk of collision with obstacles of the arm is minimized, although strictly speaking collision avoidance is exact only for the tool point. We demonstrate the implementation of this approach on the robotic assistant CORA [1], [2].

Fig. 1. The end-effector position (sphere) is shown in a world coordinate frame fixed to the working surface (z = 0). The instantaneous heading direction of the end-effector is represented by two angles relative to the vertical world axis (elevation, \( \theta \)) and the world x-axis (azimuth, \( \phi \)).

2 Attractor dynamics of end-effector motion

To generate movement trajectories of the 3D position of the end-effector of a robot arm, we use three variables (behavioral variables in the terminology of [10]). Two heading direction an-
angles, illustrated in Figure 2, are defined in terms of spherical coordinates of a coordinate frame that is centered at the end-effector and moves with it, but remains aligned relative to an arbitrary, but fixed world reference frame. The elevation, denoted $\theta$, is the angle between heading direction and the vertical axis. The azimuth, $\phi$, is the angle between the projection of heading onto the meridional plane and the arbitrary, but fixed x-axis of the world coordinate frame. The third variable is the path velocity, which is kept constant during movement.

The planned trajectory is obtained in the form of a time series of the two heading angles, $\theta(t)$ and $\phi(t)$, as the solutions of dynamical systems

\begin{align}
\tau \dot{\phi}(t) &= f(\phi) \\
\tau \dot{\theta}(t) &= g(\theta)
\end{align}

Here, the constant $\tau$ determines overall the time scale of this dynamics. The dynamical functions, $f$ and $g$, are built as sums of contributions

\begin{align}
 f(\phi) &= f_{\text{tar}}(\phi) + \sum_i f_{\text{obs},i}(\phi, \phi_i) \\
 g(\theta) &= g_{\text{tar}}(\theta) + \sum_i g_{\text{obs},i}(\theta, \theta_i)
\end{align}

that generate target acquisition ($f_{\text{tar}}$ and $g_{\text{tar}}$) and avoidance of a discrete set of obstacles ($f_{\text{obs},i}$ and $g_{\text{obs},i}$).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2}
\caption{The repulsive force-let has positive slope at $\phi - \phi_i$ and limited angular range both from a smooth Gaussian range function (dashed line) and a sharper sigmoidal cut-off function (solid line). The sharp cut-off helps delimit the influence of a repulsive force-let when multiple obstacles overlap.}
\end{figure}

2.1 Target acquisition

From the scene analysis, an estimate of the Cartesian position, $(x_{\text{tar}}, y_{\text{tar}}, z_{\text{tar}})$, of the target in the world frame is obtained. Based on the 3D position of the end-effector, $(x, y, z)$, updated at all times from the forward kinematics, the bearing of the target from the point of view of the end-effector can be expressed in spherical coordinates at follows:

\begin{align}
\phi_{\text{tar}} &= \arctan\frac{y_{\text{tar}} - y}{x_{\text{tar}} - x} \\
\theta_{\text{tar}} &= \arctan\left(\frac{z_{\text{tar}} - z}{\sqrt{(x_{\text{tar}} - x)^2 + (y_{\text{tar}} - y)^2}}\right)
\end{align}

The target contributions to the dynamics of heading direction are sinusoidal forces (to respect the angular nature of the variables):

\begin{align}
 f_{\text{tar}}(\phi) &= \lambda_{\text{tar}} \sin(\phi - \phi_{\text{tar}}) \\
 g_{\text{tar}}(\theta) &= \lambda_{\text{tar}} \sin(\theta - \theta_{\text{tar}}).
\end{align}

The parameter $\lambda_{\text{tar}}$ determines the strength of attraction toward the target and must be small relative to the obstacle contributions.

2.2 Obstacle avoidance

The scene analysis describes each obstacle (indexed by $i$) through its position, $(x_i, y_i)$, on the working surface, its maximal height, $h_i$, and its radius, $r_i$, describing its footprint approximated by an enclosing circle. For the azimuthal heading direction obstacle avoidance is implemented quite analogously to how it is done for vehicles. The angle,

$$\phi_i = \arctan\left(\frac{y_i - y}{x_i - x}\right)$$

under which the base of the obstacle in the working surface is seen from the point of view of the end-effector, repels the azimuthal heading direction. A repulsive “force-let” illustrated in Figure 2 is defined with limited angular range, so that the obstacle is sensed only as long as the end-effector is headed its way:

\begin{align}
 f_{\text{obs},i}(\phi) &= \lambda_{\text{obs}} \exp(-d_i/d_0) \\
 &\cdot \sin(\phi - \phi_i) \\
 &\cdot \exp\left[-\frac{(\phi - \phi_i)^2}{2\sigma^2}\right] \\
 &\cdot \text{range}(\phi - \phi_i, d_i).
\end{align}

The strength of repulsion, $\lambda_{\text{obs}}$, is modulated by the distance $d_i = ((y_i - y)^2 + (x_i - x)^2)^{1/2}$ between the end-effector and the obstacle, projected onto the working surface, so that an obstacles becomes repulsive only when the end-effector comes sufficiently close as scaled by the parameter, $d_0$. The angular range is determined by the angle, $\Delta\phi_i$, under which the footprint of the obstacle is seen from the end-effector position (and which depends on the distance, $d_i$, to the obstacle) augmented by a safety margin, $\delta$:

\begin{align}
\text{range}(\phi - \phi_i, d_i) &= \frac{\tanh(\alpha (\cos(\phi - \phi_i) - \cos(2\Delta\phi_i + 5))) + 1}{2}
\end{align}
where $\alpha$ is a model parameter determining how sharply the range function declines. This range function leads to a sharp cut-off beyond the boundaries of the obstacle. A smoother fall-off is superposed via the Gaussian function (width parameter, $\sigma$).

![Diagram of cylindrical obstacle (side view)](image)

Fig. 3. The computation of the elevation angle subtended by a cylindrical obstacle of known radius, height, and distance can be achieved through the Co-sinus rule.

Obstacle avoidance for the elevation component of heading direction is slightly different. The elevation of heading is repelled from the elevation, $\theta_i$, under which the base point of the obstacle in the working surface is seen from the point of view of the end-effector. The range of this repulsion is adjusted to cover the elevation angle, $\Delta \theta$, subtended by an obstacle of height, $h_i$ (see Figure 3). Obstacles are objects on the working surface and will thus not be avoided by moving below them. Therefore, the negative part of the repulsive force-let for elevation angles $\theta < \theta_i$ is set to zero, leading to an asymmetric force-let. This is relevant only when the end-effector moves toward a target in front of the obstacle, so that such low elevations are being reached. In this case, the obstacle should not affect the trajectory and this is achieved by the asymmetrical form. Except for this cut-off for negative argument, the formulae for elevation are thus strictly analogous to those for azimuth and are not repeated here.

3 Implementation on CORA

Our assistant robot CORA system has an anthropomorphic seven degree of freedom arm (Figure 4) with an eighth degree of freedom being rotation of the shoulder girdle around a vertical axis through the torso. CORA is built from a modular robotics system, in which each module has its own servo controller and communicates via a CAN-bus interface with the controlling PC. Above the trunk we assembled a two DoF pan/tilt unit carrying a stereo color camera system and microphones. The computational power is provided by a fast Ethernet network of 5 PCs with 1600Mhz Athlon CPUs running LINUX. Although CORA possesses vision algorithms that provide target coordinates [1], [2], an estimation of pose, and obstacle information, we have implemented and evaluated the attractor dynamics trajectory generation method in a first step based on obstacle and target data measured externally.

![Fig. 4. The trunk of the robotic assistant CORA is fixed to a work surface (white table). CORA’s shoulder girdle may rotate around the vertical trunk axis. From the shoulder down, CORA has an anthropomorphic 7-DoF arm. An active stereo camera system, touch-sensitive artificial skin on the two arm segments (black bands), a moment sensor in the wrist, and a microphone/speaker unit make up its sensory apparatus.](image)

3.1 Inverse kinematics

The rotation of the shoulder-girdle around a vertical axis is controlled separately by generating a constant joint velocity that brings the shoulder girdle from its initial position to an orientation perpendicular to the direction from the base of the torso to the target position. This orientation of the shoulder has been found to be best suited for grasping (not unlike the position spontaneously adopted by humans when they make manipulation movements). Three degrees of freedom describing the orientation of the tool in space are likewise controlled separately, moving them into a gripper configuration computed to be appropriate for picking up the object. The remaining four degrees of freedom still represent a redundant system with respect to the three-dimensional end-effector velocity generated from two heading direction angles and the path velocity. To solve this inverse kinematics, we used the exact solution of the inverse kinematics of 7DOF anthropomorphic arms [17]. The redundant degree of freedom can be expressed as a rotation of the elbow around an axis linking the wrist and shoulder joints. We controlled this degree of freedom independently using an algorithm, that raised the elbow as soon as the spatial position of the elbow came near an obstacle.
3.2 Numerical solution of dynamics

An Euler algorithm is used to numerically solve all differential equations defined above for the trajectory generation. In each Euler step, all parameters describing obstacle and target angles, distances, and range functions are updated, the solution of the differential equations is updated, the inverse kinematics is evaluated to transform the new end-effector velocity vector into a vector of joint velocities, and new velocity set-points are sent to the robot arm joint servos. The new Cartesian position of the end-effector is obtained by applying the forward kinematics to the new joint angle positions. The duration of the Euler step in implementation was estimated and the time scale, $\tau$, was chosen sufficiently large for this Euler step to approximate the dynamics. This is not critical, because the attractor nature of the solutions helps stabilize the numerics.

4 Results

The attractor dynamics approach generates smooth, elegant trajectories. In the absence of obstacles, these trajectories move the end-effector on a straight line to the target, imitating human movement [18]. This is useful in a robotic assistance task, as it helps non-expert users to intuitively interpret the robot’s actions and predict the movement goal.

Figure 5 shows the end-effector trajectory obtained from the attractor dynamics in a prototypical situation for which potential field solutions tend to generate spurious states. Seen from the initial spatial position of the end-effector, the target location lies behind two obstacles. The side view and a view from the top visualize how the end-effector finds its way between the obstacles as the elevation of heading direction steers the end-effector clear of the two obstacles. The sequence of photographs of the robotic assistant CORA in Figure 5 show how our solution of the inverse kinematics lifts the elbow of the robot arm when the elbow comes into the vicinity of the obstacles. Thus, as the end-effector moves toward the goal, the rest of the arm also stays free of collision.

5 Conclusion

The attractor dynamics approach to trajectory formation was generalized to the control of end-effector motion of a redundant robot arm. The two components of the heading-direction of the end-effector, the elevation and the azimuth angles, where obtained from an attractor dynamics, into which obstacles contributed repulsive force-lets. The approach was demonstrated for a robotic assistant reaching for locations on a working surface, from which obstacles protrude. We have shown, that the typical spurious states that occur in potential field methods when targets are positioned behind obstacles are avoided in the attractor dynamics approach.

We are currently linking this algorithm to online sensory information about target and obstacle coordinates to demonstrate that we can deal with moving targets and noisy sensory information. Future work will integrate this approach to movement generation with a dynamical system that organizes the interaction of the user with the robot [11].

REFERENCES
Fig. 5. The internal representation of the end-effector trajectory is shown (solid blue line) together with its heading direction in the last moment (hair on the sphere at the end of the blue line). The yellow and blue-red-transparent cylinders represent two obstacles as parametrically described for the heading direction dynamics. In (a), a frontal view from a viewpoint slightly elevated above the working surface illustrates how the elevation angle begins to deviate from the straight (constant heading) trajectory as the end-effector nears an obstacle. Elevation then steers the end-effector above the two obstacles. (b) The view from top shows how the azimuthal heading direction steers the end-effector around the two obstacles. Once the end-effector leaves the vicinity of the obstacles, the system reverts to a straight line trajectory toward the target location.