Collision-Free Coordination of Fiber Positioners in Multi-object Spectrographs

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ABSTRACT

Many fiber-fed spectroscopic survey projects, such as DESI, PFS and MOONS, will use thousands of fiber positioners packed at a focal plane. To maximize observation time, the positioners need to move simultaneously and reach their targets swiftly. We have previously presented a motion planning method based on a decentralized navigation function for the collision-free coordination of the fiber positioners in DESI. In MOONS, the end effector of each positioner handling the fiber can reach the centre of its neighbours. There is therefore a risk of collision with up to 18 surrounding positioners in the chosen dense hexagonal configuration. Moreover, the length of the second arm of the positioner is almost twice the length of the first one. As a result, the geometry of the potential collision zone between two positioners is not limited to the extremity of their end-effector, but surrounds the second arm.

In this paper, we modify the navigation function to take into account the larger collision zone resulting from the extended geometrical shape of the positioners. The proposed navigation function takes into account the configuration of the positioners as well as the constraints on the actuators, such as their maximal velocity and their mechanical clearance. Considering the fact that all the positioners' bases are fixed to the focal plane, collisions can occur locally and the risk of collision is limited to the 18 surrounding positioners. The decentralizing motion planning and trajectory generation takes advantage of this limited number of positioners and the locality of collisions, hence significantly reduces the complexity of the algorithm to a linear order. The linear complexity ensures short computation time. In addition, the time needed to move all the positioners to their targets is independent of the number of positioners. These two key advantages of the chosen decentralization approach turn this method to a promising solution for the collision-free motion-planning problem in the next-generation spectroscopic survey projects. A motion planning simulator, exploited as a software prototype, has been developed in Python. The pre-computed collision-free trajectories of the actuators of all the positioners are fed directly from the simulator to the electronics controlling the motors. A successful demonstration of the effectiveness of these trajectories on the real positioners as well as their simulated counterparts are put side by side in the following online video sequence (https://goo.gl/YuwwsE).

Keywords: Fiber positioner, MOONS, collision avoidance, coordination, decentralized navigation function

1. INTRODUCTION

Massive spectroscopic surveys are useful for measuring the redshifts of distant objects and for tracing the large-scale structure of the Universe. Many ongoing international projects aim to develop massive parallel redshift measurement instruments. These instruments will make a paradigm shift in the observation techniques compared with what is currently possible. In the next-generation of fiber-fed spectrographs such as DESI, PFS and MOONS small robotic positioners will position the fiber ends simultaneously. To insure that these instruments are used on their maximum capacity, the positioners need to share workspaces in a focal plate (Figure 1). Sharing the workspace increases the chance of collision among the adjacent positioners, which could damage the motors driving them. In our previous work,[1] we tackled this problem for positioners with two degrees of freedom and eccentric rotary joints the so-called $\theta - \phi$ design (Figure 2 (A)), where positioners had similar size arms. The

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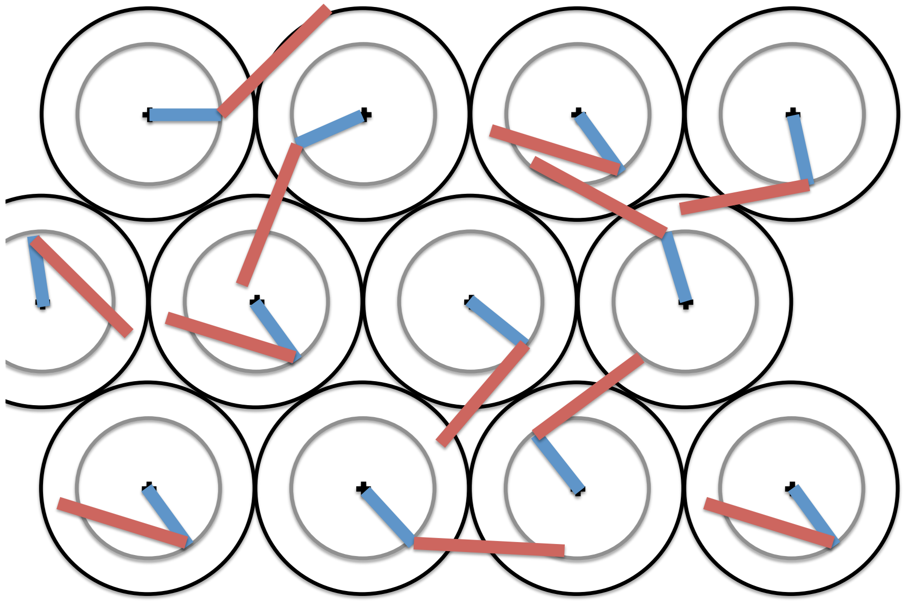

Figure 1. The positioners placed in a focal plane in a hexagonal pattern. The black circle shows the area that the base of each positioner covers on the plate. The gray circle represents the cover of the first arm. The first and the second arms of the positioners are shown in blue and red lines respectively.

proposed motion planning method is based on decentralized navigation functions (DNF). When the two arms of the positioners have the same size, the proposed trajectories guarantee deadlock-free and collision-free paths for all the fiber ends. The motion planning is decentralized in order to enable the extension of the solution for larger-scale positioners.

To increase the coverage space by the fiber-positioners, one idea is to extend the size of the second arm (Figure 1). Although this design creates a non-accessible area in the center of each positioner, it gains more accessible area on the outer part of the workspace. The scientific requirements in MOONS project for instance, promotes this design over the same-size arms. Therefore, it creates a larger risk of collision between the fiber positioners.

This paper is organized as follows. In Section 2 we briefly give the problem formulation and describe how collision-free trajectories are calculated in a general case. The modifications to adapt the potential functions for coordination of positioners with unequal arms is explained in Section 3. The simulation results corresponding to the proposed approach are presented and discussed in Section 4. Finally, in Section 5, we explore the possibilities for future research and conclude.

2. COLLISION-FREE MOTION PLANNING

For acquiring collision-free trajectories for all the positioners, we assume that target assignment can be effectively done under four main assumptions:

1. Each positioner is assigned to only one target
2. The target assigned to each positioner is always within its patrol disc and hence reachable by the positioner
3. The distance between two assigned targets is not less than a safe distance (D)
4. Every positioners starts moving from a default location that is called datum position

Thus, the focus of the work presented here is on the coordination of the positioners to avoid collision using decentralized potential functions.

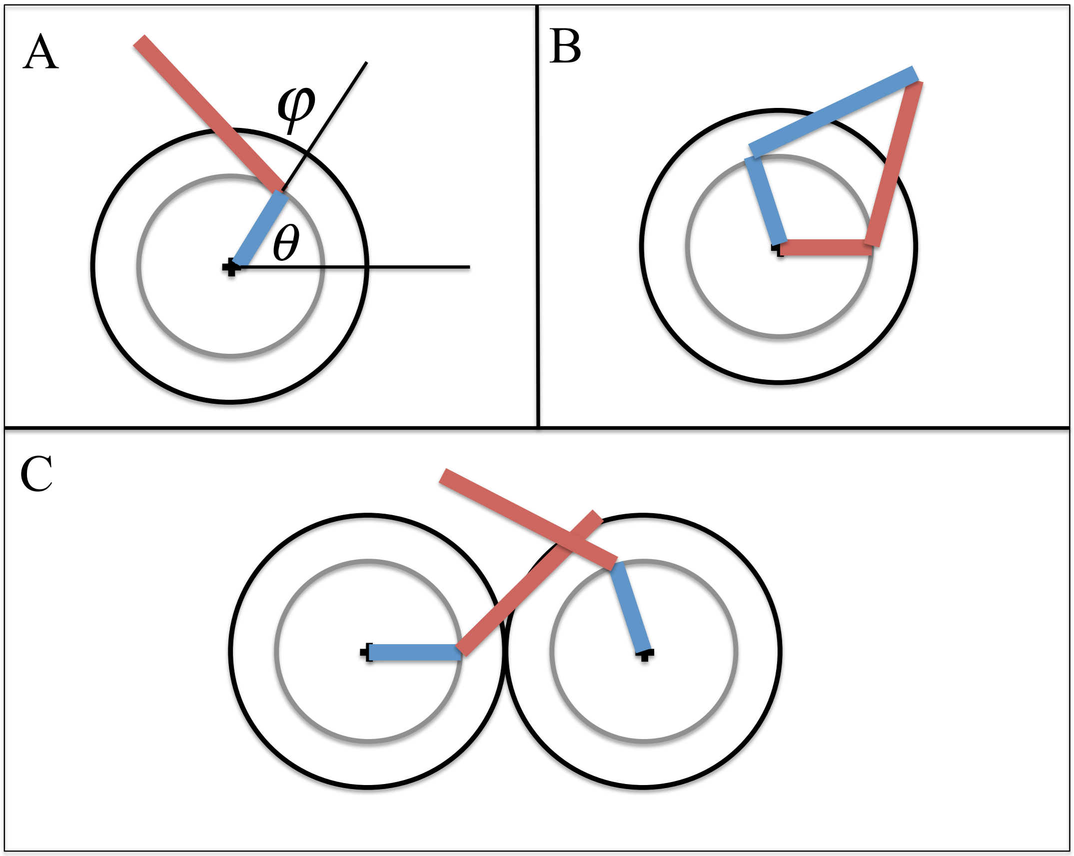

Figure 2. (A) The so-called θ,ϕ design. Each positioner has two rotary joints. (B) Two configurations that results in the fiber getting to same target. Each of the configurations is called a parity. (C) A scenario of the two positioner colliding. As each positioner can easily reach the workspace of the adjacent positioners, the risk of collision is high.

2.1 Configuration of the positioners

We consider an instrument composed of N fiber positioners. The goal of each positioner is to put its end effector that is carrying a fiber on an assigned target point. Each positioner covers a patrol area (workspace) through two rotations, θ and ϕ (Fig. 2 (A))

The forward kinematics of each fiber positioner can be described by:

$$\begin{pmatrix} x_i \\ y_i \end{pmatrix} = \begin{pmatrix} x_{ib} \\ y_{ib} \end{pmatrix} + \begin{pmatrix} cos\theta_i & cos(\theta_i + \phi_i) \\ sin\theta_i & sin(\theta_i + \phi_i) \end{pmatrix} \begin{pmatrix} l_1 \\ l_2 \end{pmatrix} \tag{1}$$

Where the position of the fiber belonging to the positioner i is $q_i = (x_i, y_i)$ in a global frame attached to the focal plane. l_1 and l_2 are first and second rotation links (arms) respectively (Fig. 2 (A)). θ and ϕ are angular positions of the two joints of the positioner i. Each positioner is controllable by its angular positions, meaning the position of each of the two motors at their gear end.

There could be two final configurations that result in the same target point. Each of these configurations, dependent of the direction of travel for θ, is called a parity (Fig. 2 (B)). The parities might be defined in the target assignment step. However, in many cases both parities are possible for the positioners. In that case, when traveling from a known configuration, reaching to one of those parities is faster considering no collision. In this work we assumed that the faster configuration is the goal configuration.

The main challenge is to coordinate the positioners to reach the predefined targets while avoiding collisions. The proposed approach should be expandable to a more large-scale problems. Currently, the ongoing projects are using thousands of positioners. The number of positioners could possibly be multiplied by ten in future projects. A centralized solution for such a problem would be practically infeasible and computationally costly due to the presence of numerous positioners and constraints ([2]). Therefore, among all the methods found in the literature for coordinating robots, we believe that decentralized and reactive control approaches are more efficient for the coordination of these positioners.

2.2 Decentralized potential functions

Inspired by the emergent behaviors among swarms (insects, birds, fishes), methods based on local reactive control have received great interest ([3]). Therefore, artificial potential fields are often exploited for the coordination of robots. In these applications the actuation torque or other inputs (e.g., the acceleration, the velocity) is derived from some potential functions that encode relevant information about the environment and the robot. In the framework of the problem presented in this paper, the use of potential functions in a decentralized scheme is promising, as it can be implemented in real-time and it also shows good flexibility with regard to adding new positioners and introducing additional constraints to the problem.

A potential function is an analytic function from the workspace of every positioner and its gradient would be attractive to its destination and repulsive from other positioners. So, an appropriate potential function could be combined with a proper control law in order to obtain a trajectory for every motor of the positioner leading to the destination and avoiding collisions.

With the focus on positioners that have same size arms, we proposed a potential function ψ_i for coordination ([1]). The potential function for positioner i is composed of two components. The first term, the attractive component, is the squared distance of the end-effector of positioner i from its target point. This term of potential function attains small values as the positioner brings the fiber closer to its target point. The second term, the repulsive component, aims at avoiding collisions between the positioner i and the six other positioners located in its vicinity. This term is activated when the two positioner robots are closer than a distance D, otherwise this term is zero. D defines the radius of a collision avoidance envelope. In this envelope the repulsive term of the potential function is activated and positioners would avoid running into each other. $d < D$ defines the radius of the safety region meaning that the two positioners would never get closer than d. The closer the two robots get, the higher values this repulsive term attains. Moving toward the minimum point of this potential function will guarantee the minimum distance of d between the positioners (Fig. 2 (C)). λ_1 and λ_2 are the two weighting parameters related to the two terms in the potential function.

$$\psi_i = \lambda_1 \left\| q_i - q_{iT} \right\|^2 + \lambda_2 \sum_{j \neq i} min(0, \frac{\left\| q_i - q_j \right\|^2 - D^2}{\left\| q_i - q_j \right\|^2 - d^2}) \tag{2}$$

According to the potential function presented in (2) and the forward kinematics defined in (1), the following control law is proposed:

$$u_i = -\nabla_{\theta_i \phi_i} \psi_i(q_i) \tag{3}$$

At each step, the positioner moves the fiber according to a gradient descent method. In order to obtain the angular velocities of each of two motors, we calculate the gradient of the potential function with respect to the angular positions of the links using the chain derivatives and the forward kinematics in (1).

$$\begin{pmatrix} \omega_{i1} \\ \omega_{i2} \end{pmatrix} = u_i = -\begin{pmatrix} \frac{\partial \psi_i}{\partial x_i}\frac{\partial x_i}{\partial \theta_i} + \frac{\partial \psi_i}{\partial y_i}\frac{\partial y_i}{\partial \theta_i} \\ \frac{\partial \psi_i}{\partial x_i}\frac{\partial x_i}{\partial \phi_i} + \frac{\partial \psi_i}{\partial y_i}\frac{\partial y_i}{\partial \phi_i} \end{pmatrix} \tag{4}$$

ω_{i1} and ω_{i2} are the angular velocity of the first and second motor of the positioner robot i respectively.

In,[1] we provided analytical proofs for collision avoidance and convergence of the positioners to their targets for DESI specifications. In this paper our aim is to modify the potential functions so that they can coordinate positioners with arms of different length.

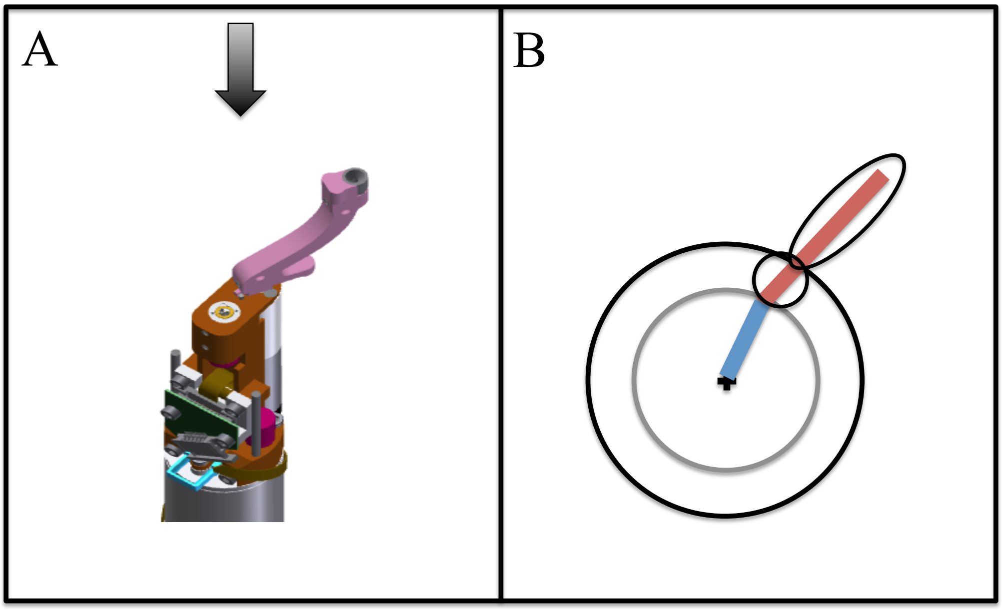

Figure 3. (A) A 3-D view of a fiber positioner. (B) The avoidance zones that correspond to two parts of the positioner that have a risk of collision.

2.3 Modification of collision avoidance zone

The concept of collision avoidance for the positioners that have arms of different sizes is very similar to the case of unique length arms. However the avoidance zones are quit different (Figure 3). The second arm is designed in a curved shape in order to facilitate the path of fiber. This results in two separated collision avoidance zones that in reality are in different heights. Therefore, each collision avoidance zone has the possibility to collide with the corresponding avoidance zone of another positioners and there is no chance that two different avoidance zones of two positioners collide because they are on differed heights.

When applying the potential function method for coordination, the only difference is the shape of the avoidance zone and collision area. When the two arm have different sizes, these zones could be represented by ellipses rather than circles (Figure 3).

When circles represent a collision zone and a conflict envelope, Euclidean distance can be best recruited to make a potential function. In case of ellipsoidal zones we need a transformation that converts the ellipses to circles and then use the same repulsive function for collision avoidance. In other words, by using weighted Euclidean distance we can achieve a transformation of the potential function. The two functions $dist(.,.)$ and $wdist(.,.)$ take the configuration of the joints of a positioner, and respectively compute the distances and the weighted distances from the center of the avoidance zone.

$$dist(p,q) = \sqrt{\sum_{i=1}^{n} (p_i - q_i)^2} \tag{5}$$

$$wdist(p,q) = \sqrt{\sum_{i=1}^{n} w_i (p_i - q_i)^2} \tag{6}$$

The values λ_1, λ_2, λ_3 are the three weighting parameters related to the three terms in the potential function.

$$\psi_i = \lambda_1 dist(q_i, q_{iT}) + \lambda_2 \sum_{j \neq i} min(0, \frac{dist^2(q_i - q_j) - D^2}{dist^2(q_i - q_j) - d^2}) + \lambda_2 \sum_{j \neq i} min(0, \frac{wdist^2(q_i - q_j) - D^2}{wdist^2(q_i - q_j) - d^2}) \tag{7}$$

According to the proposed potential function and the forward kinematics of the positioners, the following control law can move the positioners from a known position to their targets while avoiding collisions.

$$\begin{pmatrix} \omega_1 \\ \omega_2 \end{pmatrix} = \bigtriangledown_{q,i} \psi_i \tag{8}$$

Table 1 describes the motion planning algorithm. In each time step dt, each positioner computes the speed of its two motors knowing its current position and the target point as well as the position of adjacent positioners from equation 8 and calculates the position of its next move accordingly. In each time step, each positioner calls the module that computes the gradient of its potential function. So, the algorithm runs in a for-loop as many times as the number of positioners. On the other hand, the inner loop that calculates the gradient of the potential functions runs constant times (number of adjacent positioners = 18). Therefore the complexity of the algorithm will remain $O(N)$, where N is the number of positioners. Considering the fact that all the positioners' bases are fixed to the focal plane, collisions can occur locally and the chance of collision is only with the adjacent positioners. Decentralizing motion planning and trajectory generation takes advantage of the limited number of adjacent positioners and the locality of collisions and significantly reduces the complexity of the algorithm to a linear order. The low complexity of the algorithm guarantees its ease of use.

2.4 Minimizing deadlocks

The main downside of using potential based method is the introduction of local minimum points to the trajectories of the positioners. If the two positioners meet in the middle of their path, the repulsive forces will activated. In certain configurations this might result in both positioners stopping from moving further. These situations are called deadlocks. Adding noise can overcome this problem in some extends. However, duplicating the results is not feasible because of the random nature of noise. Our solution to solve some of the deadlock situations is using different size of avoidance zones for positioners. In this case, when the two positioners approach each other the positioner that have a larger avoidance zone activates the repulsive term of the potential function. However, the other positioner continues the path unless the two positioners are very near each other. The size of the avoidance zones can be pre-assigned and therefore be constant throughout the simulation. It is worth mentioning that, assigning a smaller avoidance zone to a positioner over its neighbors give an indirect priority. Meaning that the positioner could get to the target with minimum reaction to the existence of its neighbors and the risks of collisions.

3. RESULTS

To study the performance of the proposed algorithm, we conducted various sets of simulations for different numbers of positioners all in hexagonal configuration patterns. The size of positioners and the share volume between positioners are selected in a way to be compatible with next-generation spectrograph positioners such

Table 1. The list of inputs, outputs and the algorithm for coordinating fiber positioners

<table>
<tr><td colspan="2">Trajectory planning algorithm</td></tr>
<tr><td>Inputs:</td><td>Initial configurations of the position of all the positioners:
$Q_{init} = [q_1, q_2, .., q_n]$ and target position of all joints assigned to each positioner $Q_{targets} = [q_{(1,target)}, q_{(2,target)}, .., q_{(n,target)}]$</td></tr>
<tr><td>Outputs:</td><td>A sequence of motor position values for each positioner
$\Theta_1 = [\theta_1(1), \theta_1(2), , \theta_1(M)]$
$\Phi_1 = [\phi_1(1), \phi_1(2), , \phi_1(M)]$
$\Theta_2 = [\theta_2(1), \theta_2(2), , \theta_2(M)]$
$\Phi_2 = [\phi_2(1), \phi_2(2), , \phi_2(M)]$
.
.
.
$\Theta_1 = [\theta_1(1), \theta_1(2), , \theta_1(M)]$
$\Phi_1 = [\phi_1(1), \phi_1(2), , \phi_1(M)]$</td></tr>
<tr><td colspan="2">$m = 0$
repeat until $\nabla\omega = 0$
   for each positioner $(i = 1 : N)$
      $\omega_i(m) = \nabla\omega_i(q_i(m), q_{(i,target)})$
      $[\theta_i(m+1), \phi_i(m+1)] = [\theta_i(m), \phi_i(m)] + dt.\omega_i(m)$
      $m = m + 1$
      $\nabla\omega = max_i(\nabla\omega_i)$
   end for
end repeat</td></tr>
</table>

as MOONS. As expected, we observe no collision during all sets of simulations. However, some of the positioners could not get to their target points because of deadlocks. Figures 5 shows the number of positioners that are assigned to a target and the positioners that reach their targets for a set of 1025 positioners.

In realistic situations, positioners need to move their adjacent positioners. Therefore, it is expected that they will need sets of complex maneuvers in order to find a collision-free path toward their target points. Figure 4 shows snapshots of a simulation set of five positioners. The motion planning algorithm succeeds in solving the conflict by directly executing the complex maneuvers from potential fields and taking positioners to their target points. The main advantage of this method is that these types of conflicts could be solved in a decentralized manner which significantly decreases simulation time and motion duration. Therefore, the algorithm is reliable for large number of positioners.

4. CONCLUSIONS

Fiber-fed spectrograph positioners such as the ones envisioned in DESI (5000 positioner) or PFS (2400 positioners) or MOONS (1025 positioners) are already under construction. The main concept common between the designs is the use of small mechanical positioners. These positioners are responsible for moving the fiber ends toward their target points where they can observe different sets of objects such as galaxies, quasars, or stars. As the positioners share work-space, one of the many challenges is designing a motion planning algorithm that guarantees collision avoidance. Our proposed decentralized method for coordination of positioners is a potential field that ensures collision avoidance.

Our future research directions include the further minimization of deadlock situations by identifying them. By applying different avoidance zone on positioners we have already implemented an indirect schema for positioners to pass the other positioners on their way to target points. We would explore more the situations of deadlocks, in order to implement a deadlock avoidance technique preferably embedded in the potential function.

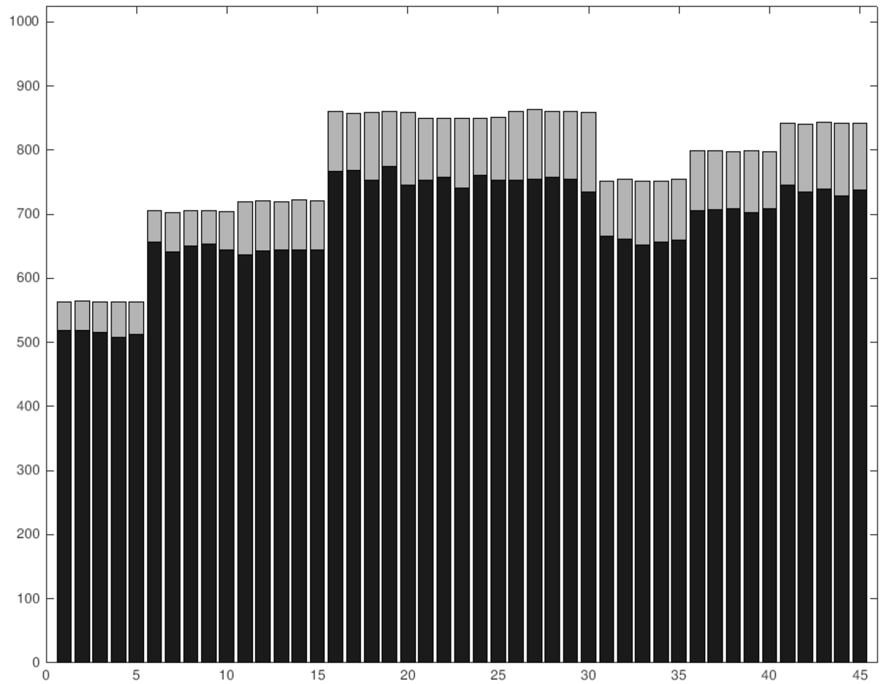

Figure 4. The number of positioners that are assigned to reach a target is shown in gray.The number of positioners that could reach their targets is shown in black.

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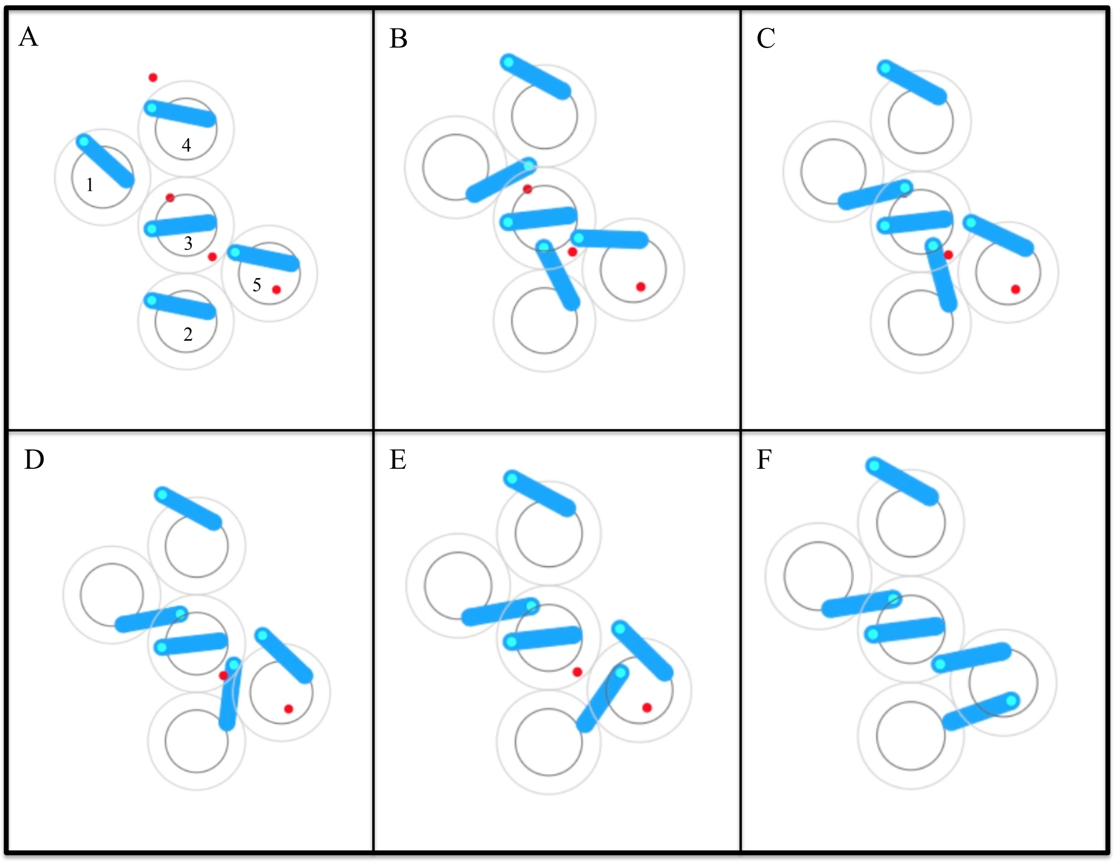

Figure 5. Six snapshots of five positioners in the move. The body of the positioners are shown by gray circles. The blue lines represent the second arm of the positioners. Red dots are targets assigned to the positioners. From (B) to (E) the positioner 5, which is very near to its target needs to get away so that the positioner 2 can pass. Once the path is clear, the positioner 5 will come back to its target (F).