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Technology **RRT*-APF Hybrid Path Planning for Reconfigurable Cable-Driven Parallel Robots**

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gradually, Artificial Potential Field (APF) is used **Hythering all and the computer and the successfully from the successfully control and the successfully.** Artificial Potential Field (APF) is used to guide the three tools eneration of random tree nodes, reducing the time **Examber 11:4** The multime to the pullar consideration and that when the rol generation of random tree nodes, reducing the time of finding the cobot will find the path, and ensuring the safe distance between the platform a **gradually, Arthural release the carrel are the reconstruction** and the cost of the reconstruction of random tree nodes, reducing the time of finding the sobstacle. But this method obstacles, and generating the shortest co generation of ration it ee iouss, reducing the eine of miding the
path, and ensuring the safe distance between the platform and
obstacles, and generating the shortest collision-free path. Post-
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sting the location of the cable connection alg
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c cable. If there is interference, optimize the robot's stiffness in the policing

mimize cable tensions to determine the optimal figuration. By adjusting the location of the cable connection

its on the fixed frame, the ob *Abstract-When* Cable-Driven Parallel Robots (CDPRs) are doing some complex work, obstacles in the environment will interfere with cables and the mobile platform. It is a meaningful work to avoid these disturbances by planning the path of CDPRs. This paper presents an optimal path planning strategy for a reconfigurable CDPR. By a variant of Rapid-exploration Random Tree (RRT) to find the optimal collision avoidance path gradually, Artificial Potential Field (APF) is used to guide the generation of random tree nodes, reducing the time of finding the path, and ensuring the safe distance between the platform and obstacles, and generating the shortest collision-free path. Postprocessing algorithm reduce the number of path points. Detect whether the generated path will cause obstacles to interfere with the cable. If there is interference, optimize the robot's stiffness and minimize cable tensions to determine the optimal configuration. By adjusting the location of the cable connection points on the fixed frame, the obstacle avoidance of the cable is realized. The simulation results demonstrate the RRT*-APF hybrid path planning algorithm's ability to successfully find the path to avoid collision of the mobile platform in the environment with obstacles, the reconstruction algorithm can find the best collision-free configuration of the cable.

Keywords-Reconfigurable cable-driven parallel robot, RRT, APF, Path planning, Obstacle avoidance*

I. INTRODUCTION

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p capacity. capacity. **Example 11** Sion-free configuration of the cable. The proposed an adaptive RI guide tree growth through F , Path planning, Obstacle avoidance expecting the more proposed and generate environments^[9]. Mishra, I. INTROD **Example 11** Keywords—**Reconfigurable cable-driven parallel robot, RRT**^{*}, guide tree growth through a
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les connected to the fixed frame. CDPRs are widely used in

Field (APF) Cable-driven parallel robots (CDPRs) are mainly composed of a fixed frame and an end-effector, end-effector is driven by cables connected to the fixed frame . CDPRs are widely used in tracking camera systems^[1], wind tunnel experiments^[2] and $\frac{1}{2}$ astronomical observation^[3-4] due to their unique advantages of lightweight design, large working space and high carrying

cables connected to the fixed frame. CDPRs are widely used in

Field (APF) guidance is used to

tracking camera systems^[1], wind tunnel experiments^[2] and

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l tracking camera systems^[1], wind tunnel experiments^[2] and

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astronomical observation^[3-4] due to their unique advantages of

lightweight design, large working space and high carryin However, because the mobile platform is driven by multiple cables, obstacles in the working environment will interfere with the mobile platform and cables when the mobile platform is moving. Therefore, it is valuable to investigate methods for avoiding collisions with obstacles either by planning the mobile platform's path or adjusting the robot's configuration.

LaValle et al. proposed the rapid-exploration random tree (RRT) algorithm commonly used in robot path planning in 1998. The RRT algorithm quickly constructs a tree structure in

and minimize cable tensions to determine the optimal will minimize the considering the beat frame, the obstacle avoidance of the cable is considering the connection of a realized. The simulation results demonstrate the RR configuration. By adjusting the location of the cable connection of a considering the connection of a realized. The simulation results demonstrate the RRT*-APF the tree and checking whether treatized. The simulation resul Fractize The simulation Festival of the calibrate the KNT^{-a} carrelate the Noondes, a better part to avoid collision of the mobile platform in the environment the RRT* algorithm to hand with obstacles, the reconstruction musing and paraming any interest the contract in the environment the RRT* algorithm to

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that when the robot enters the vicinity of the obstacle, the
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paths^[6]. Bak et al. introduced an improved RRT algorithm to
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deviation sampling algorithm to reduce the computational load
and process the resulting path to get a shorter path^[7]. In order
to improve the efficiency of RR metallity where the existion sampling algorithm to reduce the computational load
and process the resulting path to get a shorter path^[7]. In order
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algorithm is propos and process the resulting path to get a shorter path^[7]. In order to improve the efficiency of RRT algorithm, the RRT* algorithm is proposed. In the process of path optimization, by considering the connection of a new n to improve the efficiency of RRT algorithm, the RRT*
algorithm is proposed. In the process of path optimization, by
considering the connection of a new node to the parent node of
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by combining the RRT* algorithm method for CDPRs that utilizes APF-RRT* and takes motion
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Keerthi (GJK) algorithm. Then, target stability into account. Firstly, the collision detection is realized
by combining the RRT* algorithm with the Gilbert-Johnson-
Keerthi (GJK) algorithm. Then, target bias Artificial Potential
Field (APF) guidance is used to by combining the RRT* algorithm with the Gilbert-Johnson-
Keerthi (GIK) algorithm. Then, target bias Artificial Potential
Field (APF) guidance is used to shorten the convergence time
and ensure directional detection^[10] free space through random sampling and rapid exploration of the environment to generate feasible paths^[5]. Lahouar et al. introduced an algorithm for grid-based CDPR path planning, which is divided into two cases: the first case is that when the robot is not within the interference of obstacles, the robot moves directly towards the target point.; the second case is that when the robot enters the vicinity of the obstacle, the robot will find the best path without the interference of the obstacle. But this method decreases the variety of potential paths^[6]. Bak et al. introduced an improved RRT algorithm to find paths devoid of collisions for CDPRs, using the target deviation sampling algorithm to reduce the computational load and process the resulting path to get a shorter path^[7]. In order to improve the efficiency of RRT algorithm, the RRT* algorithm is proposed. In the process of path optimization, by considering the connection of a new node to the parent node of the tree and checking whether there is a shorter path that can connect the two nodes, a better path is obtained, which enables the RRT* algorithm to handle challenging path planning issues with more robustness and efficiency $[8]$. J. Xu et al. proposed an adaptive RRT* method, which can effectively guide tree growth through adaptive adjustment of sampling space and generate collision-free paths in chaotic environments^[9]. Mishra, U.A. et al. introduce a path planning method for CDPRs that utilizes APF-RRT* and takes motion stability into account. Firstly, the collision detection is realized by combining the RRT* algorithm with the Gilbert-Johnson-Keerthi (GJK) algorithm. Then, target bias Artificial Potential Field (APF) guidance is used to shorten the convergence time and ensure directional detection^[10]. However, the above path planning methods plan paths when anchor points are fixed, these methods are very effective in avoiding the interference of obstacles to the mobile platform, but in avoiding the interference of obstacles to the cable, the above method will have certain limitations.

Keerthi (GJK) algorithm. Then, target bias Artificial Potential
Field (APF) guidance is used to shorten the convergnee time
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planning methods plan paths when Field (APF) guidance is used to shorten the convergence time
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planning methods plan paths when anchor points are fixed,
these methods are very effective in avo and ensure directional detection¹⁰⁰. However, the above path
planning methods plan paths when anchor points are fixed,
these methods are very effective in avoiding the interference
of obstacles to the mobile platform, bu For traditional CDPRs, most of the interference between cables and obstacles is caused by fixed cable anchor points. Therefore, a reconfigurable CDPR with movable anchor points is developed to avoid interference between cables and obstacles by reconfiguring anchor points. Gagliardini et al. investigated the reconstruction algorithm of reconfigurable CDPR for sandblasting or spray painting in cluttered environments. Anchor points on the reconfigurable CDPR are

discrete and the cable connection points must be changed manually^[11]. Youssef et al. introduce a method to prevent collisions among cables while the mobile platform maintains the original moving trajectory. Using an algorithm to calculate the distance between two cables, when the two cables are in close proximity, it becomes necessary to ascertain which cable close proximity, it becomes necessary to ascertain which cable
is positioned higher, increase the distance from the cable below by moving the anchor point of the cable located above $up^[12]$. An, H. et al. studied a new kind of CDPR with 8 movable cable anchor points. Each cable anchor moves movable cable anchor points. Each cable anchor moves independently on the track, constantly changing the configuration of the reconfigurable CDPR to avoid obstacles and keep the mobile platform moving in its intended direction.^[13]. X. Wang et al. proposed a constrained path planning method to realize reconstruction of CDPRs, in the reconstruction process, anchor points position and cable length are adjusted to avoid obstacles. The restricted configuration space is built based on the implicit representation manifold, space is built based on the implicit representation manifold, and the loop-closure constraints are established first to realize such reconfiguration. Finally, a feasible path is found in the entire constrained configuration space by using the bidirectional rapid exploration random tree in conjunction with the designed wrench feasible detection and collision detection to ensure the forward cable tension and prevent obstacle interference^[14].

For CDPRs to complete some complex tasks that need to be operated on large equipment surfaces, such as painting and aircraft maintenance, the mobile platform needs to maintain a close distance from the operation object, and it is not enough to rely solely on path planning or to avoid obstacles through reconstruction. On this basis, this paper introduces a hybrid reconstruction. On this basis, this paper introduces a hybrid
path planning method of RRT*-APF for reconfigurable CDPRs. The interference of CDPR's mobile platform and cable mainly comes from large equipment, so large equipment is treated as obstacles in the study. Since the interference of CDPRs mainly comes from the interference of obstacles to the mobile platform and cables, two kinds of interference are solved by path planning and reconstruction respectively. solved by path planning and reconstruction respectively.
RRT* algorithm and APF algorithm are mixed to ensure that the path planning of the mobile platform is within the specified safe distance intervals of the obstacle, and OpenGJK is used to detect whether the swept body of the mobile is used to detect whether the swept body of the mobile platform and cables collide with the obstacle. When the path of the mobile platform will cause interference between cables of the mobile platform will cause interference between cables and the obstacle, but the target point must be reached because of the need to work, by moving anchor points to prevent any disturbances arising from the interaction between the cable and the surface of the equipment. We choose to minimize cable tensions while maximizing stiffness as a performance index to find the optimal reconstruction.

II. INSTITUTIONAL DESCRIPTION

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The reconfigurable CDPR structure diagram designed in this paper can be seen in the Fig. 1, which primarily comprises a fixed frame, a mobile platform, motors, cables, cable anchor devices and winches. Each cable anchor device is composed of an anchor point, a sliding block, a movable base, two guide screws and guide rails. The movable base is installed on the screws and guide rails. The movable base is installed on the guide rail and can be moved along the guide rail by the screw drive, and the anchor point is installed on the sliding block and the sliding block is driven by the screw to move on the movable base. Four motors are connected to the winch and control the winch's rotation to release or wind cables.

Fig. 1. Principle model of reconfigurable CDPR

In order to describe the spatial position relationship between mobile platform and fixed frame in reconfigurable cable-driven parallel robot system, the global coordinate system $O - XYZ$ and the local coordinate system $P - XYZ$, were established, as illustrated in Fig. 2. Fig. 1. Principle model of reconfigurable CDPR
In order to describe the spatial
between mobile platform and fixed fra
cable-driven parallel robot system, t
system $O - XYZ$ and the local coordin
were established, as illustrat

Fig. 2. Kinematics diagram of reconfigurable CDPR

P - *XYZ* is built on the mobile platform, whereas $Q - XYZ$ is built on the ground. The cable released from the winch is connected via the anchor point A_i to the connection winch is connected via the anchor point A_i to the connection point B_i on the mobile platform P . Each cable can be thought of as a straight line because it has much less mass than thought of as a straight line because it has much less mass than a mobile platform. The cable length l_i from A_i to B_i can be calculated by the following formula.

$$
l_i = \left\| a_i - \left(p + \frac{6}{P} R b_i \right) \right\| \tag{1}
$$

 $l_i = \|a_i - (p + \frac{6}{R}Rb_i)\|$ (1) *B. Stiffness matrix*
the cable anchor point's coordinate in The stiffness matrix *K* can b
esents the coordinate of the origin of static stiffness of the CDPR satisfi
z and b_i represents th $I_i = \|a_i - (p + \frac{6}{p}Rb_i)\|$ (1) *B. Stiffness matrix*
where a_i denotes the cable anchor point's coordinate in The stiffness matrix *K* can
 $O-XYZ$, *p* represents the coordinate of the origin of static stiffness of the CDPR *I_i* = $||a_i - (p + \rho Rb_i)||$ (1) *B. Stiffness matrix*

where a_i denotes the cable anchor point's coordinate in The stiffness matrix *K* can
 O-XYZ, *p* represents the coordinate of the origin of static stiffness of the C *P XYZ* in *O XYZ* and ⁱ *^b* represents the coordinate of *^B*ⁱ where the cable is connected to the mobile platform in *I_i* = $||a_i - (p + \frac{0}{p}Rb_i)||$ (1)

where a_i denotes the cable anchor point's coordinate in
 O-XYZ , *p* represents the coordinate of the origin of
 P-XYZ in *O-XYZ* and b_i represents the coordinate of B_i

where *I_R* = $||a_i - (p + \frac{6}{r}Rb_i)||$ (1) *B. Stiffness matrix*

denotes the cable anchor point's coordinate in platform's stiffness matrix *K* can be used to dep
 P represents the coordinate of the origin of static stiffness o *I*_{(a} = ||a_i - (p + °Rb)||
 O - XYZ , p represents the coordinate in the stiffness matrix *K* can be used to dep
 O - XYZ , p represents the coordinate of the origin of static stiffness under a single pose in its *L_i* = $||a_i - (p + \frac{9}{6}Rb_i)||$ (1) *B. Stiffness n*
 C a denotes the cable anchor point's coordinate in XYZ , *p* represents the coordinate of the origin of static stiffness
 XYZ, *p* represents the coordinate of the or $l_i = ||a_i - (p + \frac{6}{r}Rb_i)||$ (1) *B. Stiffness matrix*

denotes the cable anchor point's coordinate in
 p represents the coordinate of the origin of

The stiffness matrix *K* can be

patform's stiffness matrix *K* can be

pa $I_i = ||a_i - (p + \frac{6}{r}Rb_i)||$ (1) *B. Stiffness matrix*

denotes the cole anchor point's coordinate in the stiffness matrix *K* can be
 p represents the coordinate of the origin of static stiffness of the CDPR satisfies
 $O - XYZ$ $l_i = |a_i - (p + \frac{\alpha}{r}Rb_i)|$ (1) *B. Stiffness matrix*

notes the cable anchor point's coordinate in
 $l = |a_i - (p + \frac{\alpha}{r}Rb_i)|$ (1) *B. Stiffness matrix K* condenance of the origin of static stiffness under a si
 $l = -XYZ$ and b $I_i = ||a_i - (p + \frac{6}{9}Rb_i)||$ (1) *B. Stiffness matrix*

where a_i denotes the cable anchor point's coordinate in The stiffness matrix *K*
 $O - XYZ$, *p* represents the coordinate of the origin of static stiffness under a

where where a_i denotes the cable anchor points coordinate in platform's stiffness under a sing $P-XYZ$, p represents the coordinate of B_i where the cable is connected to the mobile platform in $K = -\frac{df}{dS}T - J$.
 $P-XYZ$, ${}_{\$ $I_i = |a_i - (p + \frac{\alpha}{\gamma} Rb_i)|$ (1) *B. Stiffness matrix*

notes the cable anchor point's coordinate in platform's stiffness matrix *K* corrected anchor point's coordinate of the origin of static stiffness of the CDPR s:
 $-XYZ$ lenotes the cable anchor point's coordinate in
 p represents the coordinate of the origin of
 r is the coordinate of the origin of
 R is connected to the mobile platform's stiffness of the CDPR sati
 R is the rota $l_i = ||a_i - (p + \frac{0}{2}Rb_i)||$ (1) B. Stiffness matrix K can be
 XYZ , p represents the coordinate of the origin of static stiffness matrix K can be
 XYZ , p represents the coordinate of the origin of static stiffness an $l_i = ||a_i - (p + \frac{9}{8}Rb_i)||$ (1) B. Stiffness model and the cable and hor point's coordinate in the stiffness of the cordinate of the origin of static stiffness of $O - XYZ$ and b_i represents the coordinate of B_i cable is conn where a_i denotes the cable anchor point's coordinate in *0- XYZ* , *^p* represents the coordinate of the origin of $P - XYZ$ in $O - XYZ$ and b_i represents the coordinate of B_i where the cable is connected to the mobile platform in $P - XYZ$, ${}_{P}^{O}R$ is the rotation matrix from $P - XYZ$ to *0- xyz* , which can be expressed as

$$
P - XYZ = \int_{P}^{P} R
$$
 is the rotation matrix from $P - XYZ$ to
\n $Q - XYZ$, which can be expressed as
\n
$$
\int_{P}^{Q} R = \begin{bmatrix} c \beta c \gamma & s \alpha s \beta c \gamma - c \alpha s \gamma & c \alpha s \beta c \gamma + s \alpha s \gamma \\ c \beta s \gamma & s \alpha s \beta s \gamma + c \alpha c \gamma & c \alpha s \beta s \gamma - s \alpha c \gamma \\ -s \beta & s \alpha c \beta & c \alpha c \beta \end{bmatrix}
$$
 (2)
\nwhere $c(\cdot) = \cos(\cdot)$, $s(\cdot) = \sin(\cdot)$, and α , β , γ respectively represents the Euler Angle of rotation about the X, Y and Z
\naxes.
\nThe external force operating on the mobile platform and
\nthe vrench F produced by the tension of the cables have the
\nfollowing relationship.
\n
$$
F = JT = \begin{bmatrix} u_1 & u_2 & \dots & u_n \\ r_1 \times u_1 & r_2 \times u_2 & \dots & r_n \times u_n \end{bmatrix} \begin{bmatrix} T_1 & T_2 & \dots & T_n \end{bmatrix}^T = W_e
$$
 (3
\nwhere u is the vector **expression** each cable length in write

axes. axes. $\begin{vmatrix} \n\cos \theta & \sin \theta & \sin \theta \\ \n\sin \theta & \sin \theta \\ \n\cos(\cdot), s(\cdot) = \sin(\cdot), \text{ and } \alpha, \beta, \gamma \text{ respectively} \n\end{vmatrix}$ (2) of the mobile platform $\cos(\cdot), s(\cdot) = \sin(\cdot), \text{ and } \alpha, \beta, \gamma \text{ respectively}$ resulting from $\cos(\cdot), s(\cdot) = \sin(\cdot), \text{ and } \alpha, \beta, \gamma \text{ respectively}$ resulting from $\cos(\cdot)$. Eu where $c(\cdot) = \cos(\cdot)$, $s(\cdot) = \sin(\cdot)$, and α , β , γ respectively represents the Euler Angle of rotation about the X, Y and Z

The external force operating on the mobile platform and the wrench F produced by the tension of the cables have the following relationship.

$$
F = JT = \begin{bmatrix} u_1 & u_2 & \cdots & u_n \\ r_1 \times u_1 & r_2 \times u_2 & \cdots & r_n \times u_n \end{bmatrix} \begin{bmatrix} T_1 & T_2 & \cdots & T_n \end{bmatrix}^T = W_e \tag{3}
$$

 ${}_{p}{}^{Q}R = \begin{bmatrix} c\beta s\gamma & s\alpha s\beta s\gamma + c\alpha c\gamma & c\alpha s\beta s\gamma - s\alpha c\gamma \\ -s\beta & s\alpha c\beta & c\alpha c\beta \end{bmatrix}$ (2) of the mobile platform. K_1 is

where $c(\cdot) = \cos(\cdot)$, $s(\cdot) = \sin(\cdot)$, and α , β , γ respectively resulting from a change in c

r $\begin{vmatrix} -s\beta & s\alpha c\beta & c\alpha c\beta \end{vmatrix}$ mobile platform's changin
where $c(\cdot) = \cos(\cdot)$, $s(\cdot) = \sin(\cdot)$, and α , β , γ respectively resulting from a change in
represents the Euler Angle of rotation about the X, Y and Z able co where $c(\cdot) = \cos(\cdot)$, $s(\cdot) = \sin(\cdot)$, and α , β , γ resp
represents the Euler Angle of rotation about the X,
axes.
The external force operating on the mobile platt
the wrench F produced by the tension of the cables
fol represents the Euler Angle of rotation about the X, Y and Z cable configuration.

axes.

The external force operating on the mobile platform and

the wrench F produced by the tension of the cables have the

following rela where u_n is the vector representing each cable's length in units, the mobile platform's cable connection point's position vector is represented by r_n , T_n represents the cable tension, W_e represents the external force exerted on the mobile platform.

B. Stiffness matrix

B. Stiffness matrix
The stiffness matrix *K* can be used to depict
platform's stiffness under a single pose in its work
static stiffness of the CDPR satisfies the following r Stiffness matrix
The stiffness matrix *K* can be used to depict the mobile
form's stiffness under a single pose in its workspace. The
ic stiffness of the CDPR satisfies the following relation.
 $K = -\frac{dJ}{dt}T - I\frac{dT}{dt} - K + K$ B. Stiffness matrix K can be used to depict the mobile
platform's stiffness under a single pose in its workspace. The
static stiffness of the CDPR satisfies the following relation.
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4) The stiffness matrix K can be used to depict the mobile platform's stiffness under a single pose **in** its workspace. The static stiffness of the CDPR satisfies the following relation.

$$
K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2
$$
 (4)

 $I_1 = ||a_1 - (p + \frac{6}{y}Rb_0)||$ (1) *B. Stiffness matrix*

denotes the cable anchor point's coordinate in The stiffness matrix *K* can be used to dep

p represents the coordinate of the origin of static stiffness under a singl $I_1 = ||a_1 - (p + \frac{6}{5}Rb_1)||$ (1) *B. Stiffness matrix*

lenotes the cable anchor point's coordinate in The stiffness matrix *K* can be used to p represents the coordinate of the origin of static stiffness under a single pos $\lceil \frac{\varepsilon}{\beta} \frac{\varepsilon \gamma}{\beta \gamma} \frac{\varepsilon \alpha s}{\beta \gamma - \alpha s \gamma} \frac{\varepsilon \alpha s}{\beta \gamma + s \alpha s \gamma} \rceil$ point in $P - XYZ$, $\varphi = (\alpha, \beta, \gamma)^T$ is the attitude Angle vector $\begin{vmatrix} \cos\beta s\gamma & \sin\beta s\gamma + \cos\gamma & \cos\beta s\gamma - s\alpha c\gamma \end{vmatrix}$ (2) of the mobile platform. K_1 is the stiffness that results from the $\begin{bmatrix} -s\beta & s\alpha c\beta & c\alpha c\beta \end{bmatrix}$ mobile platform's changing posture. K_2 is the stiffness XIZ in $O - XYZ$ and b_i represents the coordinate of B_i

The external force operating on the mobile platform in

XIZ, ${}_{\rho}^{0}R$ is the rotation matrix from $P - XYZ$ to
 $-XYZ$, which can be expressed as
 ${}_{\rho}^{0}R = \begin{bmatrix} c\$ where the cable is connected to the mobile platform in $K = -\frac{1}{dS}I - \frac{1}{dS}$
 $O - XYZ$, which can be expressed as
 $O - XYZ$, which can be expressed as
 $\int_{\rho}^{0} R = \begin{bmatrix} c\beta c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma \\ c\beta s\gamma & s\alpha s\beta s$ $l_i = ||a_i - (p + \gamma Rb_i)||$ (1) *B. Stiffness matrix*

otes the cable anchor points coordinate in platform's stiffness natrix *K* can be used to depicte

represents the coordinate of the origin of static stiffness of the CDPR sati Fig. $\pi = \frac{1}{2} \int_{0}^{R} \frac{1}{r} \int_{-\pi}^{R} \int_{-\pi}^{R} r \, dr \, dr = \pi/2$ in the stational candidate in platforms suffires under a single pose in is workspace.

The stationarity station sufficies under a single pose in is workspace. B. Stiffness matrix K can be used to depict the mobile
platform's stiffness under a single pose in its workspace. The
static stiffness of the CDPR satisfies the following relation.
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 X K can be used to depict the mobile

ler a single pose in its workspace. The

DPR satisfies the following relation.
 $\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 $\mathbf{x} = (x, y, z)^T$ is the coordinates of the
 $(\alpha, \beta, \gamma)^T$ is the att *Trix*
 H K can be used to depict the mobile
 S sunder a single pose in its workspace. The

the CDPR satisfies the following relation.
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 $K = (x, y, z)^T$ is the coordinates of the
 K can be used to depict the mobile
 s a single pose in its workspace. The

PR satisfies the following relation.
 $\frac{J}{S}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 $\left(\frac{J}{S}, y, z \right)^T$ is the coordinates of the
 $\left(\alpha, \beta, y \right)^T$ is the atrix K can be used to depict the mobile
under a single pose in its workspace. The
e CDPR satisfies the following relation.
 $=-\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 \int_{0}^{T} , $x = (x, y, z)^T$ is the coordinates of the
 $\varphi = (\alpha, \beta$ *B. Stiffness matrix K* can be used to depict the mobile
platform's stiffness under a single pose in its workspace. The
static stiffness of the CDPR satisfies the following relation.
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4 Thess matrix *K* can be used to depict the mobile

n's stiffness under a single pose in its workspace. The

iffness of the CDPR satisfies the following relation.
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 $S = (\mathbf{x}^T \varphi^T)^T$, *B. Stiffness matrix*

The stiffness matrix *K* can be used to depict the mobile

platform's stiffness under a single pose in its workspace. The

static stiffness of the CDPR satisfies the following relation.
 $K = -\frac{dJ}{d$ B. Stiffness matrix K can be used to depict t
platform's stiffness under a single pose in its works
static stiffness of the CDPR satisfies the following re
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$
where $S = (x^T \varphi^T)^T$, $x = (x, y,$ can be used to depict the mobile
single pose in its workspace. The
satisfies the following relation.
 $- J \frac{dT}{dS} = K_1 + K_2$ (4)
 $(x, y, z)^T$ is the coordinates of the
 β, γ ^T is the attitude Angle vector
is the stiffness th *B. Stiffness matrix*

The stiffness matrix *K* can be used to depict the mobile

platform's stiffness under a single pose in its workspace. The

static stiffness of the CDPR satisfies the following relation.
 $K = -\frac{dJ}{d$ epict the mobile
workspace. The
ving relation.
(4)
oordinates of the
de Angle vector
results from the
is the stiffness
e to a change in
s matrix can be B. Sugness matrix K can be used to depict the mobile

The stiffness under a single pose in its workspace. The

static stiffness of the CDPR satisfies the following relation.
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)

where The stiffness matrix K can be used to
platform's stiffness under a single pose in it
static stiffness of the CDPR satisfies the follo
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K$
where $S = (x^T \varphi^T)^T$, $x = (x, y, z)^T$ is the
point in $P -$ The first term K_1 of the static stiffness matrix can be
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 $K = \frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 $K = \frac{dJ}{dS}T - K_1 + K_2$ (4)
 $K = \frac{dJ}{dS}T - K_1$ $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
where $S = (x^T \varphi^T)^T$, $x = (x, y, z)^T$ is the coordinates of the
point in $P - XYZ$, $\varphi = (\alpha, \beta, y)^T$ is the attitude Angle vector
of the mobile platform. K_1 is the stiffness that results $X = (x, y, z)$ is the coordinates of the
 $= (\alpha, \beta, \gamma)^T$ is the attitude Angle vector

i. K_1 is the stiffness that results from the

anging posture. K_2 is the stiffness

ge in cable tensions due to a change in

i of the trix *K* can be used to depict the mobile

under a single pose in its workspace. The

CDPR satisfies the following relation.
 $=-\frac{dJ}{ds}T - J\frac{dT}{ds} = K_1 + K_2$ (4)
 $\varphi = (\alpha, \beta, \gamma)^T$ is the coordinates of the
 $\varphi = (\alpha, \beta, \gamma)^T$ matrix

ess matrix K can be used to depict the mobile

effness under a single pose in its workspace. The

s of the CDPR satisfies the following relation.
 $K = -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 $K^T \varphi^T \bigg)^T$, $\mathbf{x} = (x,$ trix K can be used to depict the mobile
under a single pose in its workspace. The
CDPR satisfies the following relation.
 $= -\frac{dJ}{dS}T - J\frac{dT}{dS} = K_1 + K_2$ (4)
 $\varphi = (\alpha, \beta, \gamma)^T$ is the coordinates of the
 $\varphi = (\alpha, \beta, \gamma)^T$ is Someon

Solution of plattic stiffness of the CDPR satisfies the following relation.

In the origin of

diative stiffness of the CDPR satisfies the following relation.

Platform in
 $R = -\frac{df}{dS}T - J\frac{df}{dS} - K_1 + K_2$ (4)

Pl ordinate of *B*,

platform in

platform in
 $F - \overline{X}YZ$ to
 $\Rightarrow K = 2\left(x^T \varphi^T\right)^T$, $x = (x, y, z)^T$ is the coordinates of the
 $\Rightarrow k \alpha xy$
 $\Rightarrow k \alpha xy$

point in $P - \overline{X}Z$, $\varphi = (\alpha \beta, y)^T$ is the coordinates of the
 $\alpha \alpha xy$
 α Attribution $\hat{P} = XYZ$ to where $S = (x^T \phi)^T$, $x = (x, y, z)^T$ is the coordinates of the
 $y \cos \beta \cos \gamma + \cos \gamma$
 $y \cos \beta \cos \gamma + \cos \gamma$
 $y \cos \beta \cos \gamma + \cos \gamma$
 $y \cos \beta \cos \gamma + \cos \gamma$
 $z \cos \beta$
 where $S = (x^T \varphi^T)^T$, $x = (x, y, z)^T$ is the coordinates of the resulting from a change **in** cable tensions due to a change **in** cable configuration.

The first term K_1 of the static stiffness matrix can be called platform pose stiffness.

$$
-(p + {}^{2}Rb)\parallel
$$
 (1) *B. Sitffness matrix K* can be used to depict the mobile
the coordinate of the origin of static stiffness under a single pose in its workspace. The
the coordinate of the origin of static stiffness after ODR satisfies the following relation.
*b*₁ represents the coordinate of *B₁*
*c*₁ represents the coordinate of *B₁*
and in matrix from *P*-*XYZ* to
the mobile platform in
K= $\frac{dV}{dS}T-J\frac{dT}{dS} = K_1+K_2$ (4)
and matrix from *P*-*XYZ* to
where $S = (\mathbf{x}^T \phi^T)^T$, $\mathbf{x} = (x, y, z)^T$ is the coordinates of the
positive plate, *K*₁ is the stiffness that results from the
exact *Q cas ps as as p as*

$$
y-cas\gamma \cos \beta c \gamma + sas\gamma
$$
 point in $P-XYZ$, $\varphi = (\alpha, \beta, \gamma)^T$ is the attitude Angle vector
\n $\gamma + cac\gamma \cos \beta s \gamma - sac\gamma$ point in $P-XYZ$, $\varphi = (\alpha, \beta, \gamma)^T$ is the attitude Angle vector
\n $cc\beta$ to $cac\beta$ which is the most interesting result in the same case, K_2 is the stiffness
\nsin(.) and α , β , γ respectively
\nthe problem about the X, Y and Z
\nthe first term K_1 of the static stiffness matrix can be
\ncalled platform
\nwith the tension of the cables have the
\n $K_1 = -\frac{d}{dS} \begin{pmatrix} u_1 & u_2 & \cdots & u_n \\ r_1 \times u_1 & r_2 \times u_2 & \cdots & r_n \times u_n \end{pmatrix} T =$
\n $\begin{pmatrix} u_1 & u_2 & \cdots & u_n \\ v_1 \times u_1 & r_2 \times u_2 & \cdots & r_n \times u_n \end{pmatrix} T =$
\n $\begin{pmatrix} u_1 & u_2 & \cdots & u_n \\ v_1 \times u_1 & r_2 \times u_2 & \cdots & r_n \times u_n \end{pmatrix} T =$
\n $\begin{pmatrix} u_1 & u_2 & \cdots & u_n \\ v_1 \times u_1 & v_2 \times u_2 & \cdots & v_n \times u_n \end{pmatrix} T =$
\n $\begin{pmatrix} u_1 & u_2 & \cdots & u_n \\ v_1 \times u_1 & v_2 \times u_2 & \cdots & v_n \times u_n \end{pmatrix} T =$
\n $\begin{pmatrix} u_1 & u_2 & \cdots & u_n \\ v_1 \cdot u_2 & \cdots & v_n \end{pmatrix} T =$
\n $\begin{pmatrix} u_1 & u_2 & \cdots & u_n \\ v_1 \cdot u_2 & \cdots & v_n \end{pmatrix} T =$
\n $\begin{pmatrix} u_1 & u_2 & \cdots & u_n \\ v_1 \cdot u_2 & \cdots & v_n \end{pmatrix} T =$
\n $\begin{pmatrix} v_1 & v_2 & \cdots & v_n \\ v_$

where **we** where θ and θ an

Angle of rotation about the X, Y and Z

\nThe first term
$$
K_1
$$
 of the static stiffness matrix can be called platform pose stiffness.

\nthe tension of the cables have the

\nthe tension of the cables have the

\nthe expression of the cables have the

\nthe expression of the cables have the

\nthe expression of the cables have the

\nthe direction of the cells have the

\nthe direction of the cells

ng relationship.
\n
$$
H = \begin{bmatrix} u_1 & u_2 & \cdots & u_n \\ u_1 & u_2 & \cdots & u_n \end{bmatrix} [T_1 T_2 \cdots T_n]^T = W_6 (3)
$$
\n
$$
H = \begin{bmatrix} u_1 & u_2 & \cdots & u_n \\ u_1 & u_2 & \cdots & u_n \end{bmatrix} [T_1 T_2 \cdots T_n]^T = W_6 (3)
$$
\n
$$
u_n
$$
 is the vector representation points position vector
\n
$$
u_n
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 is the vector representation points position vector
\n
$$
u_n
$$
 is the vector representation points position vector
\n
$$
= \frac{d}{dS} \begin{bmatrix} u \\ v \end{bmatrix} T_1 = \begin{bmatrix} -\frac{du}{dS} & -\frac{du}{dS} \\ -\frac{du}{dS} & \frac{dv}{dS} \end{bmatrix} = \begin{bmatrix} -\frac{du}{dS} & -\frac{du}{dS} \\ -\frac{du}{dS} & \frac{dv}{dS} \end{bmatrix} = \begin{bmatrix} -\frac{du}{dS} & -\frac{du}{dS} \\ -\frac{du}{dS} & \frac{dv}{dS} \end{bmatrix}
$$
\n
$$
= \begin{bmatrix} -\frac{du}{dS} & -\frac{du}{dS} \\ -\frac{du}{dS} & -\frac{dv}{dS} \end{bmatrix} = \frac{1}{t_1} \begin{bmatrix} -\frac{du}{t_2} & -\frac{du}{t_3} \\ -\frac{u}{t_4} & -\frac{du}{t_4} \end{bmatrix} = \begin{bmatrix} -\frac{du}{dS} & -\frac{du}{dS} \\ -\frac{du}{dS} & -\frac{dv}{dS} \end{bmatrix}
$$
\n
$$
= \begin{bmatrix} -\frac{du}{dS} & -\frac{du}{dS} \\ -\frac{du}{dS} & -\frac{dv}{dS} \end{bmatrix} = \frac{1}{t_1} \begin{bmatrix} r_x u_1 u_2 - r_y u_1 u_2 & r_x u_1 u_2 & -r_y (1 - u_2^2) - r_x u_1 u_2 \\ -r_x (1 - u_2^2) + r_x u_1 u_2 & -r_y (1 - u_2^2) - r_x u_1 u_2 & r_x (1 - u_2^2) - r_x
$$

$$
-\frac{dr}{dx} \times u = \begin{pmatrix} 0 & -u_{z} & u_{y} \\ u_{z} & 0 & -u_{x} \\ -u_{y} & u_{x} & 0 \end{pmatrix}
$$
 (6c)

$$
-\frac{dr}{d\Omega} \times u = \begin{pmatrix} r_y u_y + r_z u_z & -r_x u_y & -r_x u_z \\ -r_y u_x & r_x u_x + r_z u_z & -r_y u_z \\ -r_z u_x & -r_z u_y & r_x u_x + r_y u_y \end{pmatrix}
$$
 (6d) called

called the positional stiffness of cables.

$$
-r_{xy} - \left(\frac{x}{x} + \frac{y}{y} - \frac{y}{x}\right) \left(\frac{y}{x} + \frac{y}{x}\right)
$$
\n
$$
r_x^2 + r_y^2 - \left(r_x u_y - r_y u_x\right)^2
$$
\n
$$
-\frac{du}{dx} = \frac{1}{l_i} \begin{bmatrix} 1 - u_x^2 & -u_x u_y & -u_x u_z \\ 1 - u_y^2 & -u_y u_z \\ 1 - u_z^2 \end{bmatrix}
$$
\n(6e)\n
$$
1 - u_z^2
$$
\nthe second term K_2 of the static stiffness matrix can be the positional stiffness of cables.

\n
$$
K_2 = -J \cdot \frac{dT}{dx} = J \cdot \text{diag}\left(\frac{E_1 A_1}{l_1} - \frac{E_2 A_2}{l_2} - \frac{E_n A_n}{l_n}\right) \cdot J^\top \quad (7)
$$

2 μ μ μ λ

 $u \begin{array}{ccc} 1 & x & x & x \\ 1 & x^2 & y & x^2 \end{array}$

 $\frac{1}{2} \begin{bmatrix} 1 - u_x^2 & -u_x u_y & -u_x u_z \\ 1 - u_y^2 & -u_y u_z \\ 1 - u_z^2 \end{bmatrix}$ (6e)

 $\frac{dx}{1-u_z^2}$ $\frac{1}{1-u_z^2}$

 $1-u_z^2$

(6e)

 A_n signifies the cable's cross-sectional area, and E_n stands signifies the cable's cross-sectional area, and *^E*ⁿ A_n signifies the cable's cross-sectional area, and E_n star
for the cable's elastic modulus.
III. RRT*-APF HYBRID ALGORITHM
A. Hybrid algorithm Fies the cable's cross-sectional area, and E_n stands

s elastic modulus.

III. RRT*-APF HYBRID ALGORITHM
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 Ilgorith for the cable's elastic modulus.

III. RRT*-APF HYBRID ALGORITHM

A. Hybrid algorithm

A_n signifies the cable's cross-sectional area, and E_n
for the cable's elastic modulus.
III. RRT*-APF HYBRID ALGORITHM
A. Hybrid algorithm
In this section, combined with the actual work ne
CDPRs, a hybrid RRT*-APF *A*_n signifies the cable's cross-sectional area, and E_n stands
the cable's elastic modulus.

THE RET*-APF HYBRID ALGORITHM

IN THE RET*-APF HYBRID ALGORITHM

IN THE RET*-APF HYBRID ALGORITHM

IN this section, combined *A*_n signifies the cable's cross-sectional area, and E_n stands
for the cable's elastic modulus.

For the cable's elastic modulus.

TII. RRT*-APF HYBRID ALGORITHM
 A. Hybrid algorithm
 A. Hybrid algorithm

In this *A*_n signifies the cable's cross-sectional area, and E_n stands

for the cable's elastic modulus.

III. RRT*-APF HYBRID ALGORITHM
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III. RRT*-APF HYBR *A*_n signifies the cable's cross-sectional area, and E_n stands
for the cable's elastic modulus.
III. RRT*-APF HYBRID ALGORITHM
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III. RRT*-APF HYBRID ALGORITHM
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for the cable's elastic modulus.
III. RRT*-APF HYBRID ALGORITHM
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In this section, combined with the actual work needs of with the c *A*_a signifies the cable's cross-sectional area, and E_n stands
for the cable's elastic modulus.

III. RRT*-APF HYBRID ALGORITHM
 A. Hybrid algorithm

III. RRT*-APF HYBRID ALGORITHM
 A. Hybrid algorithm

In this se *A*_a signities the cables cross-sectional area, and E_n stands
for the cable's elastic modulus.
III. RRT*-APF HYBRID ALGORITHM
A. *Hybrid algorithm*
In this section, combined with the actual work needs of
CDPRs, a hy 10 in the cables sensuc modulus.

III. RRT*-APF HYBRID ALGORITHM

12 $\phi(X_{\text{near}}, X_{\text{obs}}) < X_{\text{up}}$

2 $\phi(X_{\text{near}}, X_{\text{obs}}) < X_{\text{up}}$

2 $\phi(X_{\text{near}}, X_{\text{obs}}) \leq X_{\text{up}}$

2 (A ϕ is a hybrid RRT*-APF algorithm

15 is smaller III. RRT*-APF HYBRID ALGORITHM
 EXECUTE ADENT ALGORITHM

In this section, combined with the actual work needs of

CDPRs, a hybrid RRT*-APF algorithm is proposed to the decreasing

determine the optimal collision-free pa A. Hybrid algorithm

In this section, combined with the actual work needs of

CDPRs, a hybrid RRT*-APF algorithm is proposed to the decreasing

determine the optimal collision-free path within the specified

safe distance In this section, combined with the actual work needs of

CDPRs, a hybrid RRT*-APF algorithm is proposed to

determine the optimal collision-free path within the specified

scale stratece interval of the obstacle surface w CDPRs, a hybrid RRT*-APF algorithm is proposed to
determine the optimal collision-free path within the specified
safe distance interval of the obstacle surface interval of the considering the cable collision. From the sta determine the optimal collision-free path within the specified

scale surface interval of the obstacle surface without

considering the cable collision. From the starting point x_{start} , magnitude decreases with in

the **Example 19** considering the cable collision. From the starting point x_{max} , magnitude decreases with increases the random tree grows, and then grows in the direction of the force's magnitude increases vertical point the random tree grows, and then grows in the direction of the

target point, constantly generating new nodes x_{new} . The target

point x_{goal} is considered reached when the new node x_{new} .'s

distance to the target point Fraction point and extended by

in the point x_{goal} is considered reached when the new nodes x_{new} . The target

distance to the target point x_{goal} is smaller than a

smaller than a

smaller than a

smaller than a

small point x_{goal} is considered reached when the new node x_{new} 's

distance to the target point x_{goal} is smaller than a

predetermined threshold value r_g . The algorithm creates the

shortest path free of collisions and bre From x_{goal} to constance the term of the smaller than $U_{\text{at}} = \frac{1}{2} \eta \rho^2 (x_{\text{near}}, x_{\text{obs}})$, $\frac{x_{\text{lower}}}{2}$

distance to the target point x_{goal} is smaller than a

spredetermined threshold value r_g . The algorithm crea Is stance to the target point x_{goal} is smaller dual a
 x x_{re} y_{c} . The algorithm creates the

hortest path free of collisions and breaks the loop. In the

potential field method (APF) is used. First, random point predeterinined uneshold value r_g . The algorithm creates the
shortest path free of collisions and breaks the loop. In the
process of generating a new node x_{new} , the hybrid artificial
a vecter
Potential field method (AP Exerce the solution of the sphere and r, as the radius. Random point x_{max} to the obstacle x_{obs} .

enerated in the ball with the goal point x_{goal} process of generating a new note x_{new} , the nyoth authority x_{new}

Potential field method (APF) is used. First, random point x_{rand} mobile platform

is generated in the ball with the goal point x_{goal} as the center attr ross-sectional area, and E_n stands

respectively according to the actual requirements, when

S-

Now $\frac{X_{\text{max}} + X_{\text{max}}}{2} < \rho(X_{\text{max}}, X_{\text{max}})$, where the obstacle, and the forces

in minimizarity in the minimizary with FINYIBRID ALGORITIM $\frac{2m}{2} = \sqrt{(\chi_{\text{max}}, \chi_{\text{obs}})} \leq \chi_{\text{upper}}$, the mobile

FINYIBRID ALGORITIM

divide netation distance after consing distance and

divide netation becomes the interesting distance and

divide netation o used. First, random point x_{rand} mobile platfo

e goal point x_{goal} as the center attraction force

dius. Random points guided by negative gradie

ed faster to find the shortest

ear that is closest to the random

t Example 1.1 and the shortest

dius. Random points guided by

regative gradie

ed faster to find the shortest

ear that is closest to the random

tree. The mobile platform is

of x_{rand} , the attraction force of

culsive fo *x* are primarization of the repulsive force of the obstacle surface without spince to the repulsive force of the obstacle surface with increasing distance men grows in the direction of the froce's magnitude decreases wit *x* riving that x_{new} is x_{new} in x_{new} in x_{new} is a constant increases with decreasing or notice x_{new} . The target attraction potential field function U_{all} is as for the new nodes x_{new} . The ting new nodes x_{new} . The target hand $U_{an} = \frac{1}{2}\pi p^2 (x_{new}, x_{obs}) + \frac{x_{new} + x_{open}}{2} \neq \rho$
 x_{new} . The algorithm creates the

media when the new node x_{new} is smaller than a
 $U_{an} = \frac{1}{2}\pi p^2 (x_{new}, x_{obs}) + \frac{x_{new} + x_{open}}{2} \neq \rho$
 The valuation to the base of the streagular coefficient

and *x_{nout}* is smaller than a
 $U_{\text{at}} = \frac{1}{2}\pi\rho^2 (x_{\text{max}}, x_{\text{obs}})$. <sup>*X_{nout}* + *X_{no}*nta coefficient

as weald, First, random point x_{max} to the obsta</sup> mal collision-free path within the specified

evental of the obstacle surface without subject to the reaction

eleccollision. From the starting point x_{new} , magnitude decre

ous, and then grows in the direction of the In this section, combined with the actual work needs of CDPRs, a hybrid RRT*-APF algorithm is proposed to determine the optimal collision-free path within the specified safe distance interval of the obstacle surface without considering the cable collision. From the starting point x_{start} , the random tree grows, and then grows in the direction of the target point, constantly generating new nodes x_{new} . The target point x_{goal} is considered reached when the new node x_{new} 's distance to the target point x_{goal} is smaller than a predetermined threshold value r_g . The algorithm creates the shortest path free of collisions and breaks the loop. In the process of generating a new node *^X new* , the hybrid artificial Potential field method (APF) is used. First, random point x_{rand} is generated in the ball with the goal point x_{goal} as the center of the sphere and *r,* as the radius. Random points guided by the target point can be selected faster to find the shortest feasible path. Find the point x_{near} that is closest to the random point among all nodes in the tree. The mobile platform is subject to the attraction force of x_{rand} , the attraction force of x_{goal} , and the attraction or repulsive force of obstacles. The attraction or repulsive forces are as follows.

The attraction force exerted by random point and target point on the mobile platform remains constant, specifically,

the target point can be selected faster to find the shortest
\nfeasible path. Find the point
$$
x_{max}
$$
 that is closest to the random
\nsubject to the attraction force of x_{max} . The mobile platform is
\nsubject to the attraction of repulsive force of obstacles. The
\nattraction or repulsive forces are as follows.
\nThe attraction force exerted by random point and target
\npoint on the mobile platform remains constant, specifically,
\n
$$
\begin{aligned}\nF_{goal} &= \frac{\left(x_{goal} - x_{near}\right)}{\left|x_{goal} - x_{near}\right|} \\
\hline\n\end{aligned}
$$
\n
$$
F_{goal} = \frac{\left(x_{goal} - x_{near}\right)}{\left|x_{total} - x_{near}\right|} \\
\hline\n\end{aligned}
$$
\n
$$
F_{total} = \frac{\left(x_{goal} - x_{near}\right)}{\left|x_{total} - x_{near}\right|} \\
\hline\n\end{aligned}
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F_{total} = \frac{\left(x_{goal} - x_{near}\right)}{\left|x_{total} - x_{near}\right|} \\
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F_{total} = \frac{\left(x_{goal} - x_{near}\right)}{\left|x_{total} - x_{near}\right|} \\
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F_{total} = \frac{\left(x_{goal} - x_{near}\right)}{\left|x_{total} - x_{near}\right|} \\
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F_{total} = \frac{\left(x_{goal} - x_{near}\right)}{\left|x_{total} - x_{near}\right|} \\
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$$
F_{total} = \frac{\left(x_{total} - x_{near}\right)}{\left|x_{total} - x_{near}\right|} \\
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F_{total} = \frac{\left(x_{total} - x_{near}\right)}{\left|x_{total} - x_{near}\right|} \\
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F_{total} = \frac{\left(x_{total} - x_{heat}\right)}{\left|x_{total} - x_{near}\right|} \\
\hline\n\end{aligned}
$$
\n
$$
F_{total} = \frac{\left(x_{total} - x_{heat}\right)}{\left|x_{total} - x_{near}\right|} \\
\hline\n\end{aligned}
$$
\n
$$
F_{total} = \frac{\left(x_{total} - x_{heat}\right)}{\left|x_{total} - x_{near}\right|} \\
\hline\n\end{aligned}
$$
\n
$$
F_{total} =
$$

The distance from the mobile platform to the obstacle

The distance from the mobile platform to the obstacle

termines whether the mobile platform receives the obstacle

extends towards the mobile platform receives the ob [$X_{\text{rand}} - X_{\text{near}}$]
The distance from the mobile platform
determines whether the mobile platform reco
attraction or repulsive force, and also
magnitude of the force. The upper limit and
safety distance interval can be set The distance from the mobile platform to the obstacle

contrinues whether the mobile platform receives the obstacle's

extends towards the mobile

corresponding to this is de

figuritied of the force. The upper limit and The distance from the mobile platform to the obstacle determines whether the mobile platform receives the obstacle's attraction or repulsive force, and also determines the magnitude of the force. The upper limit and lower limit of the safety distance interval can be set as x_{upper} and x_{lower}

determines whether the mobile platform receives the obstacle's
attraction or repulsive force, and also determines the
magnitude of the force. The upper limit and lower limit of the
safety distance interval can be set as
$$
x_{\text{upper}}
$$
 and x_{lower}
 $F_{\text{rep}} = -\nabla U_{\text{rep}}(x) = k \left(\frac{1}{\rho(x_{\text{obs}}, x_{\text{near}})} - \frac{1}{\frac{x_{\text{lower}} + x_{\text{upper}}}{2}} \right) \cdot \frac{1}{\rho^2(x_{\text{obs}}, x_{\text{near}})} x_{\text{lower}} < \rho(x_{\text{obs}}, x_{\text{near}})$
According to the above analysis, there are the following
three situations:
(1) When the distance is greater than x_{upper} , the mobile
platform is only subject to the attraction of the target point
 F_{goal} then the value of x_{new} is

According to the above analysis, there are the following three situations:

(1) When the distance is greater than x_{upper} , the mobile platform is only subject to the attraction of the target point F_{goal} then the value of x_{new} is

stands respectively according to the actual requirements , when respectively according to the actual requirements, when $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is subject to the attraction force of the obstacle, and the force's monetial in in an article i $x_{\text{lower}} + x_{\text{upper}}$ () 41 1 1

$$
\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}
$$
, the mobile platform is

spectively according to the actual requirements , when
 $\frac{1}{100}$
 $\frac{1}{2}$
 $\frac{1}{2}$ $\varphi(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is

blyect to the attraction force of the obstacle, and the force's

agnitude inc tively according to the actual requirements, when
 $\frac{+x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is

t to the attraction force of the obstacle, and the force's

tude increase with increasing distance and espectively according to the actual requirements, when $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is $\frac{1}{2}$ $\left(\frac{x_{\text{near}}, x_{\text{obs}}}{2}\right) < x_{\text{upper}}$, the mobile platform is ubject to the attraction ccording to the actual requirements, when
 $\rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is

attraction force of the obstacle, and the force's

rease with increasing distance and decreases

decreasing distance; when
 $\langle \rho(x_{\text{near}}, x_{\text{obs}}) \rangle \langle x_{\text{upper}} \rangle$, the mobile platform is
 $\langle \rho(x_{\text{near}}, x_{\text{obs}}) \rangle \langle x_{\text{upper}} \rangle$, the mobile platform is

attraction force of the obstacle, and the force's

crease with increasing distance and decreases

dec respectively according to the actual requirements, when $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is subject to the attraction force of the obstacle, and the force's magnitude increase with inc respectively according to the actual requirements , when $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is subject to the attraction force of the obstacle, and the force's magnitude increases with i respectively according to the actual requirements, when
 $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is

subject to the attraction force of the obstacle, and the force's

magnitude increase with ly according to the actual requirements, when

per $\langle \rho(x_{\text{near}}, x_{\text{obs}}) \rangle \langle x_{\text{upper}} \rangle$, the mobile platform is

the attraction force of the obstacle, and the force's

e increase with increasing distance and decreases

decr spectively according to the actual requirements, when
 $\frac{1}{2} \times \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is
 $\frac{1}{2} \times \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is

blyect to the attraction force of the obst the section of the actual requirements the subsemum of the actual requirements of the obstacle, and the force's ith increasing distance; when $\frac{x_{\text{lower}} + x_{\text{upper}}}{2}$, the mobile platform is $\frac{x_{\text{lower}} + x_{\text{upper}}}{2}$, the mobi respectively according to the actual requirements , when $x_{\text{lower}} + x_{\text{upper}} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is a subject to the attraction force of the obstacle, and the force's magnitude increase with incre $x_{\text{lower}} < \rho(x_{\text{near}}, x_{\text{obs}}) < \frac{x_{\text{lower}} + x_{\text{upper}}}{2}$, the mobile platform is tively according to the actual requirements, when
 $+x_{upper}$
 $\ge \rho(x_{near}, x_{obs}) < x_{upper}$, the mobile platform is

to the attraction force of the obstacle, and the force's

itude increase with increasing distance and decreases

decr respectively according to the actual requirements, when $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is subject to the attraction force of the obstacle, and the force's magnitude increase with inc respectively according to the actual requirements , when $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is subject to the attraction force of the obstacle, and the force's magnitude increase with in respectively according to the actual requirements , when $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is subject to the attraction force of the obstacle, and the force's magnitude increase with in respectively according to the actual requirements, when $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is subject to the attraction force of the obstacle, and the force's magnitude increase with inc ectively according to the actual requirements, when $\frac{e^{-\lambda}X_{upper}}{2} < \rho(x_{new}, x_{obs}) < x_{upper}$, the mobile platform is ect to the attraction force of the obstacle, and the force's the increasing distance and decreases with increas rely according to the actual requirements , when
 $\frac{upper}{upper} < \rho(x_{near}, x_{obs}) < x_{upper}$, the mobile platform is

o the attraction force of the obstacle, and the force's

de increase with increasing distance and decreases

decreasing *x* the actual requirements , when
 $) < x_{\text{upper}}$, the mobile platform is

orce of the obstacle, and the force's

increasing distance and decreases

distance; when
 $\frac{x + x_{\text{upper}}}{2}$, the mobile platform is

orce of the obst spectively according to the actual requirements , when

<u>sower + x_{upper} </u> $\lt \rho(x_{\text{near}}, x_{\text{obs}}) \lt x_{\text{upper}}$, the mobile platform is

bject to the attraction force of the obstacle, and the force's

universe with increasing respectively according to the actual requirements, when
 $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$, the mobile platform is

subject to the attraction force of the obstacle, and the force's

magnitude increase with with decreasing distance and decreasing distance when
 $x_{lower} < \rho(x_{near}, x_{obs}) < \frac{x_{lower} + x_{upper}}{2}$, the mobile platform is

subject to the repulsive force of the obstacle, and the force's

magnitude decreases with increasing distanc the actual requirements , when
 $1 < x_{upper}$, the mobile platform is

rece of the obstacle, and the force's

increasing distance and decreases

distance;
 $\frac{1}{2}$, the mobile platform is
 $\frac{1}{2}$
 $\frac{1}{2}$, the mobile pl exactual requirements , when

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distance; when

of the obstacle, and the force's

easing distance The obstacle, and the force's

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distance; when
 $\frac{d\mathbf{r}}{dt}$, the mobile platform is

the obstacle, and the force's

sing distance; conversely, the

the decreasing distance. The
 U_{att} i attraction force of the obstacle, and the force's
rease with increasing distance and decreases
decreasing distance; when
decreasing distance; when
 x_{wbs} / $x_{\text{lower}} + x_{\text{upper}}$, the mobile platform is
repulsive force of rease with increasing distance and decreases
decreasing distance; when
decreasing distance; when
 x_{sys} $(x_{source} + x_{upper}$, the mobile platform is
repulsive force of the obstacle, and the force's
reases with increasing distance; $x_{\text{near}}, x_{\text{obs}}$ / < x_{upper} , the mobile platform is
action force of the obstacle, and the force's
se with increasing distance and decreases
creasing distance; when
 s , $\frac{x_{\text{lower}} + x_{\text{upper}}}{2}$, the mobile platform is
ul 1 force of the obstacle, and the force's
th increasing distance; the force's
th increasing distance; when
 $\frac{mg}{2}$, the mobile platform is
 $\frac{2}{2}$ force of the obstacle, and the force's
thi hiercasing distance. The
thi subject to the attraction force of the obstacle, and the force's magnitude increase with increasing distance and decreases with decreasing distance; when subject to the repulsive force of the obstacle, and the force's magnitude decreases with increasing distance; conversely, the force 's magnitude increases with decreasing distance. The

attraction potential field function U_{at} is as follows.

$$
U_{\text{att}} = \frac{1}{2} \eta \rho^2 \left(x_{\text{near}}^{\text{}} , x_{\text{obs}}^{\text{}} \right), \frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho \left(x_{\text{near}}^{\text{}} , x_{\text{obs}}^{\text{}} \right) < x_{\text{upper}} \tag{9}
$$

 $V_{\text{lower}} < \rho\left(x_{\text{near}}, x_{\text{obs}}\right) < \frac{x_{\text{lower}} + x_{\text{upper}}}{2}$, the mobile platform is
subject to the repulsive force of the obstacle, and the force's
magnitude decreases with increasing distance; conversely, the
orce's magnitude i $x_{\text{lower}} < \rho(x_{\text{near}}, x_{\text{obs}}) < \frac{\rho(x_{\text{near}}, x_{\text{obs}})}{2}$, the mobile platform is
subject to the repulsive force of the obstacle, and the force's
magnitude decreases with increasing distance; conversely, the
force's magnitude in subject to the repulsive \angle
magnitude decreases with increasing distance; conversely, the
force's magnitude increases with decreasing distance. The
attraction potential field function U_{att} is as follows.
 $U_{\text{att}} = \$ magnitude decreases with increasing distance; conversely, the
force's magnitude increases with decreasing distance. The
direction potential field function U_{att} is as follows.
 $U_{\text{att}} = \frac{1}{2} \eta \rho^2 (x_{\text{near}}, x_{\text{obs}}), \frac{x$ x_{near} , x_{obs}), $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$ (9)
proportional gain coefficient, $\rho(x_{\text{near}}, x_{\text{obs}})$ as
ssents the distance from the mobile platform
stacle x_{obs} . The direction originates fro $\langle x_{\text{near}}, x_{\text{obs}} \rangle$, $\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho(x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$
proportional gain coefficient, $\rho(x_{\text{near}}, x_{\text{obs}})$
ssents the distance from the mobile platt
stacle x_{obs} . The direction originates from
m and ext distance; when
distance; when
distance; when
f the obstacle, and the force's
saing distance; conversely, the
ith decreasing distance. The
 $1 U_{\text{att}}$ is as follows.
 $+ x_{\text{upper}} < \rho (x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}$ (9)
n coefficient, The repulsive potential field function *U*_{rep} is as the repulsive potential field function U_{ren} , $\frac{X_{\text{obs}}}{X_{\text{obs}}}$ as U_{en} to the obstacle x_{obs} . The direction originates from the bile platform and ext $\rho(x_{\text{near}}, x_{\text{obs}})$ as
mobile platform
ginates from the
obstacle. The
lerived from the
ld.
,
,
(10)
per
is as follows where η is the proportional gain coefficient, $\rho(x_{\text{near}}, x_{\text{obs}})$ as a vector, Represents the distance from the mobile platform x_{near} to the obstacle x_{obs} . The direction originates from the mobile platform and extends towards the obstacle. The attraction force F_{att} corresponding to this is derived from the negative gradient of the attraction potential field.

$$
F_{\text{att}} = -\nabla U_{\text{att}}(x) = \eta \rho (x_{\text{near}}, x_{\text{obs}}),
$$

$$
\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho (x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}
$$
 (10)

The repulsive potential field function U_{rep} is as follows

$$
(x_{\text{near}}, x_{\text{obs}}) < \frac{x_{\text{lower}} + x_{\text{upper}}}{2},
$$
 the mobile platform is
to the repulsive force of the obstacle, and the force's
e decreases with increasing distance; conversely, the
magnitude increases with decreasing distance. The
potential field function U_{att} is as follows.

$$
-7\eta \rho^2 (x_{\text{near}}, x_{\text{obs}}), \frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho (x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}
$$
 (9)
is the proportional gain coefficient, $\rho (x_{\text{near}}, x_{\text{obs}})$ as
Represents the distance from the mobile platform
the obstacle x_{obs} . The direction originates from the
plafform and extends towards the obstacle. The
force F_{att} corresponding to this is derived from the
gradient of the attraction potential field.

$$
F_{\text{att}} = -\nabla U_{\text{att}} (x) = \eta \rho (x_{\text{near}}, x_{\text{obs}}),
$$
 (10)

$$
\frac{x_{\text{lower}} + x_{\text{upper}}}{2} < \rho (x_{\text{near}}, x_{\text{obs}}) < x_{\text{upper}}
$$
 (10)
spulsive potential field function U_{rep} is as follows

$$
U_{\text{rep}} = \frac{1}{2}k \left(\frac{1}{\rho (x_{\text{obs}}, x_{\text{near}})} - \frac{1}{\frac{x_{\text{lower}} + x_{\text{upper}}}{2}} \right)^2, \quad (11)
$$

$$
x_{\text{lower}} < \rho (x_{\text{obs}}, x_{\text{near}}) < \frac{x_{\text{lower}} + x_{\text{upper}}}{2} \quad \text{is a constant and } \rho (x_{\text{obs}}, x_{\text{near}}) \quad \text{is a vector,}
$$
ing the distance from the mobile platform x_{near} to the
 x_{obs} , the direction originates from the obstacle and
owards the mobile platform. The repulsive force F_{rep}

subject to the repulsive force of the obstacle, and the force's
smagnitude decreases with increasing distance; conversely, the
force's magnitude increases with increasing distance; conversely, the
force's magnitude increa The repulsive potential field function U_{rep} is as follows
 $U_{\text{rep}} = \frac{1}{2}k \left(\frac{1}{\rho(x_{\text{obs}}, x_{\text{near}})} - \frac{1}{\frac{x_{\text{lower}} + x_{\text{upper}}}{2}} \right)^2$,
 $x_{\text{lower}} < \rho(x_{\text{obs}}, x_{\text{near}}) < \frac{x_{\text{lower}} + x_{\text{upper}}}{2}$

where k is a constant and $\rho(x_{$ The repulsive potential field function U_{rep} is as follows
 $U_{\text{rep}} = \frac{1}{2}k \left(\frac{1}{\rho(x_{\text{obs}}, x_{\text{near}})} - \frac{1}{\frac{x_{\text{lower}} + x_{\text{upper}}}{2}} \right)^2$,
 $x_{\text{lower}} < \rho(x_{\text{obs}}, x_{\text{near}}) < \frac{x_{\text{lower}} + x_{\text{upper}}}{2}$

where k is a constant and $\rho(x_{$ $U_{\text{rep}} = \frac{1}{2}k \left(\frac{1}{\rho(x_{\text{obs}}, x_{\text{near}})} - \frac{1}{\frac{x_{\text{lower}} + x_{\text{upper}}}{2}} \right)^2$ (11)
 $x_{\text{lower}} < \rho(x_{\text{obs}}, x_{\text{near}}) < \frac{x_{\text{lower}} + x_{\text{upper}}}{2}$

where *k* is a constant and $\rho(x_{\text{obs}}, x_{\text{near}})$ is a vector,

representing the distance fro $U_{\text{rep}} = \frac{1}{2}k \left(\frac{1}{\rho(x_{\text{obs}}, x_{\text{near}})} - \frac{1}{\frac{x_{\text{lower}} + x_{\text{upper}}}{2}} \right)$, (11)
 $x_{\text{lower}} < \rho(x_{\text{obs}}, x_{\text{near}}) < \frac{x_{\text{lower}} + x_{\text{upper}}}{2}$ (11)

where k is a constant and $\rho(x_{\text{obs}}, x_{\text{near}})$ is a vector, representing the distance f $U_{\text{rep}} = \frac{1}{2}k \left(\frac{1}{\rho(x_{\text{obs}}, x_{\text{near}})} - \frac{1}{\frac{x_{\text{lower}} + x_{\text{upper}}}{2}} \right)$,
 $x_{\text{lower}} < \rho(x_{\text{obs}}, x_{\text{near}}) < \frac{x_{\text{lower}} + x_{\text{upper}}}{2}$

where k is a constant and $\rho(x_{\text{obs}}, x_{\text{near}})$ is a vecto

representing the distance from the mob by now λ_{max} , the trying in the basis of the control of the galaxies from the control of the galaxies of the control of the c $\left\{\n\begin{aligned}\nF_{\text{rand}} &= \frac{(x_{\text{rand}} - x_{\text{near}})}{\|x_{\text{rand}} - x_{\text{near}}\|}\n\end{aligned}\n\right.\n\quad\n\text{where } k \text{ is a constant and } \rho(x_{\text{obs}}, x_{\text{near}}) \text{ is a vector,}\n\end{aligned}\n\right.$ where $k \text{ is a constant and } \rho(x_{\text{obs}}, x_{\text{near}})$ is a vector, representing the distance from the mobile plat x_{obs} , x_{upper}
 $\frac{1}{x_{\text{lower}} + x_{\text{upper}}}\n \frac{1}{2}$, (11)
 $\frac{x_{\text{lower}} + x_{\text{upper}}}{2}$, (11)
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 x_{obs} , x_{near}) is a vector,

bile platform x_{near} to the

es from the obstacle and

The repulsive force attraction or repulsive force of obstacles. The

pulsive forces are as follows.

pulsive forces are as follows.

Figure 1. The repulsive potential field function U_{xy} is as follows

bille platform remains constant, sp *x x* x_{max}
 x $V_{\text{avg}} = \frac{1}{2}k \left(\frac{1}{\rho(x_{\text{obs}}, x_{\text{max}})} - \frac{1}{\frac{x_{\text{lower}} + x_{\text{upper}}}{x_{\text{lower}}}} \right)^2$, (11)
 $x_{\text{max}} = \frac{1}{2}k \left(\frac{1}{\rho(x_{\text{obs}}, x_{\text{max}})} - \frac{1}{\frac{x_{\text{lower}} + x_{\text{upper}}}{x_{\text{upper}}}} \right)^2$, (11)
 $x_{\text{max}} = \frac{1}{2}k \left(\frac{1$ bases in the tree. The mobile electromic state of X_{max} and $Y_{max} = X_{max}$.
 $\frac{Y_{max} - Y_{max}}{Y_{max}}$ (12)
 $\frac{Y_{max}}{Y_{max}} = \frac{Y_{max} - Y_{max}}{Y_{max}}$ (13)
 $\frac{Y_{max}}{Y_{max}} = \frac{Y_{max} - Y_{max}}{Y_{max}}$ (13)
 $\frac{Y_{max}}{Y_{max}} = \frac{Y_{max} - Y_{max}}{Y_{max}}$ (13)
 \frac $\frac{1}{\rho(x_{obs}, x_{near})} - \frac{1}{\frac{x_{lower} + x_{upper}}{2}}$, (11)
 $\frac{x_{obs}, x_{near}}{2} < \frac{x_{lower} + x_{upper}}{2}$ (11)
 $\frac{x_{obs}, x_{near}}{2} < \frac{x_{lower} + x_{upper}}{2}$

mstant and $\rho(x_{obs}, x_{near})$ is a vector, ance from the mobile platform x_{near} to the irrection originates obstacle x_{obs} , the direction originates from the obstacle a
extends towards the mobile platform. The repulsive force *F*
corresponding to this is derived from the negative gradient
the repulsive potential field.
 $\frac{1}{\$ representing the distance from the mobile platform x_{near} to the obstacle x_{obs} , the direction originates from the obstacle and extends towards the mobile platform. The repulsive force F_{rep} corresponding to this is derived from the negative gradient of the repulsive potential field.

$$
\left(\frac{1}{\rho(x_{\text{obs}}, x_{\text{near}})} - \frac{1}{\frac{x_{\text{lower}} + x_{\text{upper}}}{2}}\right) \cdot \frac{1}{\rho^2(x_{\text{obs}}, x_{\text{near}})} x_{\text{lower}} < \rho(x_{\text{obs}}, x_{\text{near}}) < \frac{x_{\text{lower}} + x_{\text{upper}}}{2} \tag{12}
$$

$$
xnew = xnear + vstep \cdot Fgoal
$$
 (13)

where v_{step} is the step size.

(2) When the distance is greater than $\frac{x_{\text{lower}} + x_{\text{upper}}}{2}$ (2) When the distance is greater than $\frac{x_{\text{lower}} + x_{\text{upper}}}{2}$ and less than x_{upper} , the mobile platform is subjected to the force F_{res1} of unit size in the resultant direction of the attraction force F_{goal} along the target point, the attraction force F_{rand} of random points and the attraction force F_{att} of obstacles, then the value of x_{new} is

$$
x_{\text{new}} = x_{\text{near}} + v_{\text{step}} \cdot F_{\text{res1}} = x_{\text{near}} + v_{\text{step}} \cdot \frac{\left(F_{\text{goal}} + F_{\text{rand}} + F_{\text{att}}\right)}{\left\|F_{\text{goal}} + F_{\text{rand}} + F_{\text{att}}\right\|} (14)
$$

(3) When the distance is greater than x_{lower} and less than lower $\mathcal{N}_{\text{upper}}$ $\overline{\mathbf{c}}$ $\frac{x_{\text{lower}} + x_{\text{upper}}}{2}$, the mobile platform is subjected to the force F_{res2} of unit size in the resultant direction of the attraction force F_{goal} along the target point, the attraction force F_{rand} of random points and the obstacle's repulsive force F_{at} , then the value of x_{new} is

$$
x_{\text{new}} = x_{\text{near}} + v_{\text{step}} \cdot F_{\text{res2}} = x_{\text{near}} + v_{\text{step}} \cdot \frac{\left(F_{\text{goal}} + F_{\text{rand}} + F_{\text{rep}}\right)}{\left\|F_{\text{goal}} + F_{\text{rand}} + F_{\text{rep}}\right\|} (15)
$$

In the field of x_{near} , find the node x_{best} with shorter path cost, and then replace x_{near} with x_{best} to connect with x_{new} , calculate the distance the mobile platform is from the obstacle, and determine whether it is a safe distance. If it is not, continue to find the next parent node, and if there is no parent node conforming to the safe distance, abandon x_{new} and rebuild.

% &ROOLVLRQ GHWHFWLRQ B. Collision detection

This section mainly introduces the collision detection method of mobile platform. In this paper, OpenGJK fast detection algorithm^[15] is adopted to detect obstacle collision, so as to achieve faster and more accurate collision detection. OpenGJK fast detection algorithm can calculate the distance between two convex polyhedra, approximate the mobile platform and obstacles as convex polyhedra, for the cylinder, can calculate the distance from the mobile platform to the obstacle and the central axis of the cylinder, minus the radius of the cylinder is the distance from the surface of the cylinder. For a mobile platform, to ensure a safe distance from the obstacle on the path from x_{start} to x_{goal} , it is necessary to determine whether the swept body of the mobile platform can maintain a safe distance from the obstacle between two nodes. The convex hull algorithm is used to determine the swept body of the mobile platform. As illustrated in Fig. 3, it is the schematic diagram of collision between the swept body of the mobile platform and the obstacle and maintaining a safe distance.

Fig. 3. Schematic diagram of collision between mobile platform and obstacle

& 3DWK SRVWSURFHVVLQJ C. *Path post-processing*

After the collision-free path of the mobile platform is obtained, it goes through a post-processing process. The skimmed body is generated from the initial point and subsequent path points in turn, and the safe distance between the skimmed body and the mobile platform is judged until the initial point is connected to the farthest path point conforming to the safe distance, and the middle path point is abandoned. With the farthest path point conforming to the safety distance as the initial point, repeat the above steps until the connection to the target point, and complete the post-processing of the resulting path. As illustrated in Fig. 4, this process can effectively reduce the number of path points and obtain a simpler collision-free path.

Fig. 4. Schematic diagram of path post-processing process

IV. RECONFIGURATION STRATEGY OF CABLE-DRIVEN PARALLEL ROBOT

The collision-free path of the mobile platform has been obtained in the previous section. The path of the mobile platform from x_{start} to x_{goal} is discretized into *n* path points, expressed as

$$
x = \left[x_{\text{start}}, x_1, x_2, \cdots, x_{\text{goal}} \right]
$$
 (16)

Since the cable can only be pulled and cannot be pushed, the lower limit of tension T_{\min} should be greater than zero, and the upper limit of tension should be restricted by the motor's maximum torque. The working space of a CDPR is usually irregular and limited by tension boundaries. Therefore, when a mobile platform performs a task, the path may include points that are not in the workspace, and the mobile platform cannot safely reach the path point without changing the location of anchor points. Another problem is that in the process of moving the platform to some necessary positions, obstacles may interfere with the cable, causing serious consequences. Therefore, it should be ensured that the distance between the swept body of the cable and the obstacle during the movement is exceeds the minimum safe distance D_{\min} , and the cable anchor points' positions should be changed to avoid the interference caused by the obstacle to the cable. As illustrated in Fig. 5, the collision between the swept body of the cable and the obstacle and the safe distance are respectively schematic diagrams.

(b) No collision

Fig. 5. Schematic diagram of collision between a cable sweep and an obstacle

In this section, Particle Swarm Optimization (PSO) algorithm is used to calculate the optimal position of each anchor point in the configurable region while maintaining the collision free path of the mobile platform. To obtain a suitable refactoring solution, we consider two objectives. The first objective is to minimize the total cable tensions, as this metric is closely linked to the reconfigurable CDPR's power consumption. Maximizing the stiffness of the reconfigurable CDPR is the second objective. Therefore, the objective function is written as

$$
F(T,K) = \min\left(\frac{\sum_{i=1}^{n} T_i}{\|K\|}\right) \tag{17}
$$

The constraint is set to:

$$
\begin{cases}\nT_{\min} < T < T_{\max} \\
D_{\min} < D\n\end{cases}
$$
\n
$$
X_{\min} < X_i < X_{\max} \\
Y_{\min} < Y_i < Y_{\max} \\
JT = W_e\n\tag{18}
$$

 T_{min} and T_{max} respectively represent the cable tension's lower and upper limits. D and D_{\min} are the distance and lower limit of distance of cable and obstacle respectively. X_i , X_{imin} and X_{imax} are the X coordinates, lower and upper limits of X coordinates of the *ith* anchor point in $O - XYZ$, respectively. Y_i , Y_{min} and Y_{max} are respectively the Y coordinate, lower and upper limits of Y coordinates of the *ith* anchor point in $O - XYZ$. The aforementioned reconstruction problems are resolved using the PSO algorithm, whose computation procedure is illustrated in Fig 6.

Fig. 6. Reconstruction algorithm diagram

Reconfigurable CDPR can be considered as a collection of CDPRs with different configuration of anchor points, which will increase the working space of the robot to a certain extent. The algorithm will calculate in advance whether the next path point satisfies the cable tension's upper and lower limits, and whether the distance from cables to the obstacle during the movement to the next point is greater than the specified safety distance. If both meet the requirements, the reconstruction will not be triggered. If one item does not meet the requirements, the reconstruction will be triggered, and cable anchor points will be reconfigured before the mobile platform starts to run to the next path point.

V. **SIMULATION EXPERIMENT**

Simulation is performed to assess the proposed path planning algorithm's performance and reconstruction method. The fixed frame of the CDPR is a cuboid frame with a size of $2m$, 1.5m and 1.8m, and the mobile platform is a cube with a size of $0.2m$, $0.2m$ and $0.1m$ and a weight of 1kg. The anchor points' original positions are set at the corners of the fixed frame, and the first anchor point's reachable position is X_1 [0, 0.95], Y_1 [0, 0.7], the second anchor point's reachable position is X_2 [1.05, 2], Y_2 [0, 0.7], the third anchor point's reachable position is $X_1[1.05, 2]$, $Y_1[0.8, 1.5]$, the fourth anchor point's reachable position is X_4 [0, 0.95], Y_4 [0.8, 1.5], The minimum and maximum permissible cable tension is established at 1N and 300N, respectively.

In order to prove the proposed path planning algorithm's efficacy, the obstacle in the environment is modeled as a cylinder with a radius of $0.25m$ and a length of $1m$, with the two endpoints of the central axis of the cylinder located at $(0.5, 0.75, 0.5)$ and $(1.5, 0.75, 0.5)$, the safe distance from the mobile platform to the obstacle is set within the range of $0.01m$ to $0.02m$.

Firstly, the proposed RRT*-APF hybrid algorithm is used to obtain the desired approach optimal path from the starting x_{start} [1.4, 0.75, 1.32] point to the target point $x_{\text{total}}[1.4, 1.115, 1]$ in an environment with cylindrical obstacles. Fig. 7a and Fig. 7b show the collision-free path and the post-processed path from x_{start} to x_{goal} respectively. The post-processing algorithm successfully reduces the number of path points from 32 to 7. Fig 8a and Fig 8b respectively show the distance from the mobile platform to the obstacle in the path from x_{start} to x_{goal} before post-processing and after postprocessing. The red line is the set safe distance interval. It can be seen from the figure that the mobile platform is within the safe distance interval during the whole path process.

Fig. 7. Simulated environmental result

Fig. 8. Distance between the mobile platform and the obstacle

Regarding cables, when the sixth path point is reached by the mobile platform, cables 1 and 2 will collide with the obstacle. Reconstruction begins when the mobile platform reaches the fifth path point. After the reconstruction of cable anchor points is completed, the mobile platform will continue to move the remaining path points until the target point is reached. Fig. 9a and Fig. 9b respectively show the positions of cord points before and after reconstruction. Fig. 10 shows the distance from the four cables to the obstacle in the path from x_{start} to x_{goal} , and the red line is the set safe distance threshold. It can be seen from the figure that the four cables are all at a safe distance during the whole path process.

Fig. 9. Reconstruction result

Fig. 10. Distance between cable and obstacle

VI. CONCLUSION

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the robot stiffness and minimizing the sum of cable tensi Transport System[C] *N* Proceedings that Sacrosom Figuration of maximizing

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Trim **In** this paper, a RRT*-APF hybrid path planning algorithm is proposed for reconfigurable CDPR. By guiding the generation of random tree nodes by APF, from the starting point to the destination, determine the best viable path that avoids collisions. For the path points where obstacles will interfere with cables, the optimal configuration of maximizing the robot stiffness and minimizing the sum of cable tensions is selected based on the cable tensions and distance detection. The obstacle avoidance of the cable is realized by adjusting the anchor point positions. The proposed path planning algorithm's effectiveness is confirmed through simulation

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