Mechanism Optimization of A New Integrated
 Leg for Legged Robots

Yansong Song, Xinyu Zhao, Xianyue Gang, Hui Chai, Peng Fu
 Abstract—The leg mechanism holds considerable mobile power sources have been developed by **Significance for the load-bearing and lightweight design of**
the log Technology (Fig. 10)
the load-bearing and lightweight design of
the load-bearing and lightweight design of the load-bearing and lightweight design of th IAENG International Journal of Applied Mathematics

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Mathematic Ariven legged robotic platforms equipped

legged Robots. France Integrated Integrations and quasi-static force balance equations for the leg and integration and means of the load-bearing and lightweight design of institute of Technology (11).
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 to address the instability challenges in extreme operations
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legged robots. Herein, an integrated leg system was** Yansong Song, Xinyu Zhao, Xianyue Gang, Hui Cl
 Mostract—The leg mechanism holds considerable mobile power sources

significance for the load-bearing and lightweight design of Institute of Technology

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significance for the load-bearing and lightweight design of

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ligged robots. Herein, an integrated leg syst **design variables,** have the results show that the optimized increases the significance for the load-bearing and lightweight design of listitute of Technology [10] legged robots. Herein, an integrated leg system was constr *Abstract***—The leg mechanism holds considerable mobile ower sources have significance for the load-bearing and lightweight design of Institute of Technology [10] legeled robots. Herein, an integrated leg system was const** *mechanism* holds considerable mobile power sugginficance for the load-bearing and lightweight design of Institute of Technol legged robots. Herein, an integrated leg system was constructed Deffense Technology environmen **Consider the degree in the mechanism** holds considerable mobile power sources are algorithment and lightweight design of linstitute of Technology to address the instability challenges in extreme operational Defense Techno *Index Terms*—legged robot, integrated leg, mechanism

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integrated regions in extreme operational

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intermation methods, the exp Egged robot, internal, an integrated and properational and direct respectively chaldlenges in extreme operational environments. Utilizing the vector algebra and linear transformation methods, the explicit geometric analysi Ing the vector argeora and inear

nods, the explicit geometric analysis

tatic force balance equations for the leg

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with the coordinates of joint points as the

ing to an optimized The maism were established. Subsequently, an optimization

hel was proposed with the coordinates of joint points as the

gla variables, leading to an optimized structural layout for

leg mechanism. The results show that th

Manism were established. Subsequently, an optimization

el wariables, leading to an optimized structural layout for

leg mechanism. The results show that the optimized leg

leg mechanism effectively reduces the peak force model was proposed with the coordinates of joint points as the

design variables, leading to an optimized structural layout for

the leg mechanism effectively reduces the peak force of the hydraulic

eylinder, thereby enha Usegal variances, reaumy of an optimized structural rayout for
the leg mechanism. The results show that the optimized leg
mechanism effectively reduces the peak force of the hydraulic
expirated results expansion, minimize The restriction of the restriction of the byth and the political of the political eylinder, thereby enhancing its extreme load-bearing capacity.
 Index Terms—legged robot, integrated leg, mechanism

optimization, minimize maximum

I. INTRODUCTION

These platforms are hig

demonstrate versatility by tr **Index Terms—legged robot, integrated leg, mechanism**
 optimization, minimize maximum

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I. INTRODUCTION These platforms are

demonstrate versatility by traversing diverse terrains

with adept d *Index Terms*—legged robot, integrated leg, mechanism

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These platforms are

demonstrate versatility by traversing diverse terrains

with adept detection and obstacle avoidance capabilities [1].

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Hydraulically driven legged robots, as an **Headle Example 1** I. INTRODUCTION These platforms are hydraulic-
demonstrate versatility by traversing diverse terrains existing research regarding quide with adept detection and obstacle avoidance capabilities [1].
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I. INTRODUCTION These platforms are

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with adept detection and obstacle avoidance capabilities [1].

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andaptability to non-state demonstrate versatility by traversing diverse terrains

with adept detection and obstacle avoidance capabilities [1].

Hydraulically diven legged \blacksquare demonstrate versatility by traversing diverse terra
with adept detection and obstacle avoidance capabilities [
Hydraulically driven legged robots, as an important rol
type, boost advantages of high power density an th adept detection and obstacle avoidance capabilities [1]. This compared to the diversity and strong beta train field operation capsumum objets, as an important robot extern field operation caps, boost advantages of high Hydraulically driven legged robots, as an important robot

type, boost advantages of high power density and strong

adaptability compared to other drive methods [2]. In this case,

legged robots have been developed by the type, boost advantages of high power density and strong
adaptability compared to other drive methods [2]. In this case,
alegged robots have attracted considerable academic attention
worldwide. Specifically, Mosher [3] Intr uck", opening up a new path for the development of
draulic-driven robots. Representatives such as robots
cluding BigDog and Atlas developed by Boston Dynamic,
d HyQ developed by the Italian Institute of Technology
ree intr Frack , opening up a new path of the development of Shandong Unive
hydraulic-driven robots. Representatives such as robots approach to cyli
including BigDog and Atlas developed by Boston Dynamic, treamlines the h
and HyQ d mydraulic-driven robots. Representatives such as robots

including BigDog and Atlas developed by Boston Dynamic,

and HyQ developed by the Italian Institute of Technology

were introduced in [4]-[7].

In recent years, nume FOR dynamic working environments, legged robots
daptability to non-
demonstrate versatility by traversing diverse terrains
adaptability to non-
existing research reg

gangxianyue@sdut.edu.cn). gects in Shandong under Grant 20191ZZY020317, the National Natural

ence Foundation Project of China under Grant 20203191, the Natural

ence Foundation of Shandong under Grant ZR2020ME140.

Then, the objectiv

Yansong Song Science Foundation Project of China under Grant 62073191, the Natural

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Yansong Song is a graduate of School of Transportation and Vehicle

(e-mail: songys199891@ Franson Shandong under Grant ZR2020ME140.

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interference, were d

Xinyu Zhao is a gra Yansong Song is a graduate of School of Transportation and Vehicle

Engineering, Shandong University of Technology, Zibo, 255000 PR China.

(e-mail: songys199891@163.com).

Xianyu Zhao is a graduate of School of Transporta

hydraulic-driven legged robotic platforms equipped with hydraulic-driven legged robotic platforms equipped with mobile power sources have been developed by Harbin Institute of Technology [8]-[9], National University of **on Samual Mean School**
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hydraulic-driven legged robotic platforms equipped with
mobile power sources have been developed by Harbin
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Institute-driven legged robotic platforms equipped with
mobile power sources have been developed by Harbin
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hydraulic-driven legged robotic platforms equip

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motion, various hydraulic-driven quadruped robots
Shareholm and Hydrobots
These platforms are highlighted for their excellent
adaptability to non-standard road conditions. Grounded in
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motion, various hydraulic-driven quadruped robots wi adaptability to non-standard road conditions. Grounded in
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motion, various hydraulic-driven quadruped robots with
certain field operation capability, such as SCalf existing research regarding quadruped robots and biomimetic
motion, various hydraulic-driven quadruped robots with
certain field operation capability, such as SCalf and SCalf-II,
have been developed by the Robotics Researc motion, various hydraulic-driven quadruped robots with
certain field operation capability, such as SCalf and SCalf-II,
have been developed by the Robotics Research Center of
Shandong University [12].
The leg mechanism serv certain field operation capability, such as SCalf and SCalf-II,
have been developed by the Robotics Research Center of
Shandong University [12].
The leg mechanism serves as the cornerstone for
controlling both the gait and have been developed by the Robotics Research Center of Shandong University [12].
The leg mechanism serves as the cornerstone for controlling both the gait and stability of the entire legged robot system [13]-[14]. The Robo Shandong University [12].
The leg mechanism serves as the cornerstone for
controlling both the gait and stability of the entire legged
robot system [13]-[14]. The Robotics Research Center of
Shandong University has recentl The leg mechanism serves as the cornerstone for controlling both the gait and stability of the entire legged robot system [13]-[14]. The Robotics Research Center of Shandong University has recently proposed an innovative a ntrolling both the gait and stability of the entire legged
bot system [13]-[14]. The Robotics Research Center of
andong University has recently proposed an innovative
proach to cylinder-leg integration (Fig. 2). This solut robot system [13]-[14]. The Robotics Research Center of Shandong University has recently proposed an innovative approach to cylinder-leg integration (Fig. 2). This solution streamlines the hydraulic circuitry of the robot Shandong University has recently proposed an innovative
approach to cylinder-leg integration (Fig. 2). This solution
streamlines the hydraulic circuitry of the robot and achieves a
reduction in mass by incorporating the hy approach to cylinder-leg integration (Fig. 2). This solution
streamlines the hydraulic circuitry of the robot and achieves a
reduction in mass by incorporating the hydraulic cylinders
directly within the framework. Zong [1 streamlines the hydraulic circuitry of the robot and achieves a
reduction in mass by incorporating the hydraulic cylinders
directly within the framework. Zong [15] has found that
single-leg weight reduction can be as signi

reduction in mass by incorporating the hydraulic cylinders
directly within the framework. Zong [15] has found that
single-leg weight reduction can be as significant as 10%.
However, the compact design of the leg mechanism directly within the framework. Zong [15] has found that
single-leg weight reduction can be as significant as 10%.
However, the compact design of the leg mechanism can result
in suboptimal performance, particularly under ex single-leg weight reduction can be as significant as 10
However, the compact design of the leg mechanism can res
in suboptimal performance, particularly under extre
working conditions such as navigating steep slopes
initia wever, the compact design of the leg mechanism can result
suboptimal performance, particularly under extreme
orking conditions such as navigating steep slopes or
tiating movement from a prone position.
Herein, the kinemati in suboptimal performance, particularly under extreme
working conditions such as navigating steep slopes or
initiating movement from a prone position.
Herein, the kinematic and quasi-static dynamics analyses
of the new int working conditions such as navigating steep slopes or
initiating movement from a prone position.
Herein, the kinematic and quasi-static dynamics analyses
of the new integrated leg mechanism were initially carried out.
Then initiating movement from a prone position.

Herein, the kinematic and quasi-static dynamics analyses

of the new integrated leg mechanism were initially carried out.

Then, the objective function, optimization variables, a Herein, the kinematic and quasi-static dynamics analyses
of the new integrated leg mechanism were initially carried out.
Then, the objective function, optimization variables, and
design constraints, such as spatial dimensi

including BigDog and Atlas developed by Boston Dynamic,

and HyQ developed by the Italian Institute of Technology

reduction in mass

were introduced in [4]-[7].

In recent years, numerous universities and research

instit and HyQ developed by the Italian Institute of Technology
were introduced in [4]-[7].
In recent years, numerous universities and research single-leg weight rest
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Projects in Shandong under Grant 201 stitutes have conducted extensive research on singue-reg-weight red
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hydraulic-driven legged robots. For instance, in suboptimal perfo

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Work vas supported in part by the Major Science and Technology Innovation

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analysis of the integrated leg linkage configuration. Section $\begin{cases} x_s \\ y_s \end{cases}$
V establishes the optimization model for the integrated leg
mechanism optimization by present **IAENG International Journal of Applied Mathematic**

analysis of the integrated leg linkage configuration. Section

V establishes the optimization model for the integrated leg

mechanism. Section VI illustrates the effect **IAENG International Journal of Applied Mathematic

analysis of the integrated leg linkage configuration. Section

V establishes the optimization model for the integrated leg

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V establishes the optimization model for the integrated leg
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V establishes the optimization model for the integrated leg

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analysis of the integrated leg linkage configuration. Section

V establishes the optimization model for the integrated leg

mechanism optimization by presenting a case **IAENG International Journal of Applied Mat**

analysis of the integrated leg linkage configuration. Section

V establishes the optimization model for the integrated leg

mechanism. Section VI illustrates the effectiveness **IAENG International Journal of Applied**

integrated leg linkage configuration. Section

is the optimization model for the integrated leg

Section VI illustrates the effectiveness of the

ptimization by presenting a case

E *D*

of joint point *S* and joint point *D*

os $\varphi = \frac{x_s - 3}{L_{DS}}$
 $\therefore \varphi = \sqrt{1 - \cos(\omega t)}$
 $\therefore \varphi = \sqrt{1 - \cos(\omega t)}$

Fig. 2 Integrated single-leg mechanism diagram

The integrated leg mechanism, as depicted in Fig. 2. The
 the frame. The end point *^M* of the hydraulic cylinder *MN* is **Example 19** is a separate on the distances between
 A
 Example 1999 Example 1999 hip subsets of the horizontal movement of the hydraulic cylinder

Fig. 2 Integrated single-leg mechanism diagram

The integrated leg mechanism, as depicted in Fig. 2. The knowing L_{cs} , β :

hinge points *D*, *C*, *S M* sin $\varphi = \sqrt{\frac{K}{K}}$ *M* diven the distances bet
 H Given the distances bet
 M distance by the cordinates of
 M and *DS* can be derive
 N and *IS* and *IS* can be derive
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Fig. 2 Integrated single-leg mechanism diagram

The integrated leg mechanism, as depicted in Fig. 2. The

hinge points D, C, S, and E form the hip joint of the leg

mechanis Fig. 2 Integrated single-leg mechanism diagram

Fig. 2 Integrated single-leg mechanism diagram

CS and DS c

hinge points D, C, S, and E form the hip joint of the leg

mechanism. Among them, hinge points D and E are hing

The coordinates of joint point
 $X_{\mathbf{B}}$ or $X_{\mathbf{B}}$ or $X_{\mathbf{B}}$ or $Y_{\mathbf{B}}$ and $Y_{\mathbf{B}}$ are coordinates of joint point
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 $X_B \overline{Y}_B$ \overline{Y}_K
 \overline{Y}_B \overline{Y}_K

Fig. 3 Integrated leg linkage configuration

III. KINEMATIC GEOMETRY ANALYSIS Eqs. (1-7) were explice

The integrated leg linkage configuration

The in $X_B \overrightarrow{P}$ and $X_B \overrightarrow{P}$ and Y_N is a constant, because of the Pythagorean Theorem:
 $\begin{pmatrix} x_N \\ y_N \end{pmatrix}_G = \begin{pmatrix} x_N \\ y_C \end{pmatrix}_G$

Fig. 3 Integrated leg linkage configuration

III. KINEMATIC GEOMETRY ANALYSIS and power beriz $\begin{bmatrix} x_N \\ y_N \end{bmatrix}_G = \begin{bmatrix} x_N \\ y_N \end{bmatrix}_G = \begin{bmatrix} x_N \\ y_C - \sqrt{N} \end{bmatrix}$

Fig. 3 Integrated leg linkage configuration

III. KINEMATIC GEOMETRY ANALYSIS can only move horizontally.

The integrated leg linkage configuration is shown Fig. 3 Integrated leg linkage configuration

Fig. 3 Integrated leg linkage configuration

can only move horiz

III. KINEMATIC GEOMETRY ANALYSIS Eqs. (1-7) were

The integrated leg linkage configuration is shown in Fig. 3. **EXERCISE ON THE CONSULTER CONSULTS AND USE AND THE VALUATION THE PRESENTATION THE INTERNATIC GEOMETRY ANALYSIS Eqs. (1-7) were explicitly for The integrated leg linkage configuration is shown in Fig. 3. direct determinat** Fig. 3 Integrated leg linkage configuration

III. KINEMATIC GEOMETRY ANALYSIS

The integrated leg linkage configuration is shown in Fig. 3. direct determination of

The global coordinate system xEy took the joint point E Fig. 3 IMERIMATIC GEOMETRY ANALYSIS can only move horizontally.

The integrated leg linkage configuration is shown in Fig. 3. direct determination of the The global coordinate system xEy took the joint point *E* as speci The integrated leg linkage configuration is shown in Fig. 3. direct determination of the geobal coordinate system *xEy* took the joint point *E* as
the origin, vertically downward as the positive direction of their roots The integrated leg linkage configuration is shown in Fig. 3.

The global coordinate system xEy took the joint point *E* as

the origin, vertically downward as the positive direction of

the x-axis, and horizontally to th For the Pythagorean The

Legated leg linkage configuration

Legated leg linkage configuration

Exerced leg linkage configuration

Exerced leg linkage configuration

C WATIC GEOMETRY ANALYSIS Eqs. (1-7) were exerced in the **Example 18**
 Example 18
 Example 18
 Example 18
 Example 18
 EXATIC GEOMETRY ANALYSIS
 EXATIC GEO direction of the y-axis. The positive direction of the z-axis
was hereby determined by the right-hand rule. To solve the
coordinates of each hinge point, the swing angle θ between
the positive direction of the x-axis a coordinates of each hinge point, the swing angle θ between equations, the moment M_E the positive direction of the x-axis and *EI* was taken as a employed as the input, while input parameter to construct the functiona the positive direction of the x-axis and *EI* was taken as a employed as the input, while
input parameter to construct the functional relationship cylinder *MN* was adopted as the
between *c* coordinates of each joint poi input parameter to construct the functic
between the coordinates of each joint poin
angle θ .
The coordinates of joint point *I* were as
swing angle θ :
 $\begin{cases} x_I \\ y_I \end{cases} = L_{EI} \begin{cases} \cos \theta \\ \sin \theta \end{cases}$
where the subscript "G

$$
\begin{Bmatrix} x_I \\ y_I \end{Bmatrix}_{\text{G}} = L_{EI} \begin{Bmatrix} \cos \theta \\ \sin \theta \end{Bmatrix} \tag{1}
$$

$$
\begin{cases} x_{S} \\ y_{S} \end{cases}_{G} = L_{ES} \begin{cases} \cos(\theta - \alpha) \\ \sin(\theta - \alpha) \end{cases}
$$
 (2)

matics
 $L_{ES}\begin{cases} \cos(\theta-\alpha) \\ \sin(\theta-\alpha) \end{cases}$ (2)

body coordinate system $x_B F y_B$ was

int point *S* as the origin, *DS* as the

straight line perpendicular to *DS* as

enotes the rotation angle from the $\cos(\theta-\alpha)$
 $\sin(\theta-\alpha)$ (2)

rdinate system $x_B F y_B$ was

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ate system $x_B F y_B$ was

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 $\begin{cases} x_s \\ y_s \end{cases} = L_{ES} \begin{cases} \cos(\theta-\alpha) \\ \sin(\theta-\alpha) \end{cases}$ (2)

3, a body coordinate system $x_B F y_B$ was

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the straight line perpendicular to *DS* as **athematics**
 $\begin{cases} x_s \\ y_s \end{cases} = L_{ES} \begin{cases} \cos(\theta-\alpha) \\ \sin(\theta-\alpha) \end{cases}$ (2)

3, a body coordinate system $x_B F y_B$ was

and joint point S as the origin, DS as the

1 the straight line perpendicular to DS as
 φ denotes the rotatio of Applied Mathematics
 $\begin{cases} x_s \\ y_s \end{cases} = L_{ES} \begin{cases} \cos(\theta-\alpha) \\ \sin(\theta-\alpha) \end{cases}$ (2)

As shown in Fig. 3, a body coordinate system $x_B F y_B$ was

tablished by taking joint point *S* as the origin, *DS* as the

rizontal axis, and the **al of Applied Mathematics**
 $\begin{cases} x_s \\ y_s \end{cases} = L_{ES} \begin{cases} \cos(\theta-\alpha) \\ \sin(\theta-\alpha) \end{cases}$ (2)

As shown in Fig. 3, a body coordinate system $x_B F y_B$ was

established by taking joint point *S* as the origin, *DS* as the

horizontal axis **horizontal axis, and the straight line straight line straight line perpendicular of** *L***_{ES}** $\begin{cases} x_s \\ \sin(\theta-\alpha) \end{cases}$ **(2) As shown in Fig. 3, a body coordinate system** $x_\text{B}Fy_\text{B}$ **was established by taking joint point** *S* **al of Applied Mathematics**
 $\begin{cases} x_s \\ y_s \end{cases} = L_{ES} \begin{cases} \cos(\theta-\alpha) \\ \sin(\theta-\alpha) \end{cases}$ (2)

As shown in Fig. 3, a body coordinate system $x_B F y_B$ was

established by taking joint point *S* as the origin, *DS* as the

horizontal axis **al of Applied Mathematics**
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As shown in Fig. 3, a body coordinate system $x_B F y_B$ was

established by taking joint point *S* as the origin, *DS* as the

horizontal **al of Applied Mathematics**
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As shown in Fig. 3, a body coordinate system $x_B F y_B$ was

established by taking joint point *S* as the origin, *DS* as the

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As shown in Fig. 3, a body coordinate system $x_B F y_B$ was

established by taking joint point *S* as the origin, *DS* as the

horizontal axis, and the straight lin $\begin{cases} x_s \\ y_s \end{cases} = L_{ES} \begin{cases} \cos(\theta - \alpha) \\ \sin(\theta - \alpha) \end{cases}$ (2)

3, a body coordinate system $x_B F y_B$ was

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 $L_{ES}\left\{\cos(\theta-\alpha)\right\}$ (2)
 $\sin(\theta-\alpha)$ (2)
 Ddy coordinate system $x_B F y_B$ was

point *S* as the origin, *DS* as the

aight line perpendicular to *DS* as

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x-axis of the global coordi **In thematics**
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 y_s\n \end{cases} = L_{ES} \begin{cases}\n \cos(\theta-\alpha) \\
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2. 3, a body coordinate system $x_B F y_B$ was

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d the straight line perpendicular to *DS* as
 φ deno As shown in Fig. 3, a body coordinate system $x_B F y_B$ was
tablished by taking joint point *S* as the origin, *DS* as the
rizontal axis, and the straight line perpendicular to *DS* as
exertical axis. φ denotes the rotat established by taking joint point *S* as the origin, *DS* as the horizontal axis, and the straight line perpendicular to *DS* as the vertical axis. φ denotes the rotation angle from the positive direction of the x-axi *CS* and *DS* as the vertical axis, and the straight line perpendicular to *DS* as the vertical axis. φ denotes the rotation angle from the positive direction of the x-axis of the global coordinate system *xEy* to *DS* $\begin{cases} x_s \\ y_s \end{cases} = L_{ES} \begin{cases} \cos(\theta-\alpha) \\ \sin(\theta-\alpha) \end{cases}$ (2)
As shown in Fig. 3, a body coordinate system $x_p F y_p$ was
established by taking joint point *S* as the origin, *DS* as the
orizontal axis, and the straight line perpendic $\begin{cases} x_s \\ y_s \end{cases} = L_{ES} \begin{cases} \cos(\theta - \alpha) \\ \sin(\theta - \alpha) \end{cases}$ (2)

g. 3, a body coordinate system $x_B F y_B$ was

ting joint point *S* as the origin, *DS* as the

d the straight line perpendicular to *DS* as
 φ denotes the rotation $\begin{cases}\ny_s\end{cases}\n_s = L_{ES}\left\{\sin(\theta-\alpha)\right\}$ (2)

g. 3, a body coordinate system $x_B F y_B$ was

sing joint point *S* as the origin, *DS* as the
 φ denotes the rotation angle from the

1 of the x-axis of the global coordinate

1 of system x_B of the coordinate of $\int_{X} x_B$ in $\sqrt{2}x_B$. Then, x_B in the coordinate transformation equation is $\int_{V_C} \left[\frac{1}{6} \int_{V_E} \left[\frac{f_V}{g} \right]_{V_E} \right]_{V_C}$ (6) $\int_{V_C} \left[\frac{f_V}{g} \left[\frac{f_V}{g} \right]_{V_E} \right]_{V_C}$ (6) $\int_{$

$$
\cos \varphi = \frac{x_S - x_D}{L_{DS}}\tag{3}
$$

$$
\sin \varphi = \sqrt{1 - \cos^2 \varphi} \tag{4}
$$

knowing L_{CS} , β : $\cos \varphi = \frac{x_s - x_b}{L_{DS}}$ (3)
 $\sin \varphi = \sqrt{1 - \cos^2 \varphi}$ (4)

Given the distances between *C*, *D*, and *S* in the retracted

state of hydraulic cylinders, the included angle β between
 CS and *DS* can be derived. In the body Given the distances between *C*, *D*, and *S* in the retracted
state of hydraulic cylinders, the included angle β between
x_BFy_B, the coordinates of joint point *C* can be derived by
knowing L_{CS} , β :
 $\begin{cases} x_C$ of joint point *S* and joint point *D* as:
 $\cos \varphi = \frac{x_s - x_b}{L_{DS}}$ (3)
 $\sin \varphi = \sqrt{1 - \cos^2 \varphi}$ (4)

Given the distances between *C*, *D*, and *S* in the retracted

state of hydraulic cylinders, the included angle β betwee $\frac{-x_D}{\cos^2 \varphi}$ (3)
 $\frac{\cos^2 \varphi}{\csc^2 \varphi}$ (4)

in *C*, *D*, and *S* in the retracted

in the body coordinate system

int point *C* can be derived by
 $\sin \beta$
 $\sin \beta$

is $\sin \beta$

is $\sin \beta$

is $\sin \beta$

is $\cos \varphi$ (5)
 $\sin \$ as:
 $\frac{p^2}{r^2 \varphi}$ (3)
 $\frac{p^3}{r^2 \varphi}$ (4)
 \therefore D, and S in the retracted

ncluded angle β between

ne body coordinate system

point C can be derived by
 $\cos \beta$
 $\sin \beta$ (5)

ents the body coordinate

nt point C Freehold of the x -axias of the global

y to DS. It could be derived from the coordinates

nt S and joint point D as:
 $\cos \varphi = \frac{x_s - x_p}{L_{DS}}$ (3)
 $\sin \varphi = \sqrt{1 - \cos^2 \varphi}$ (4)

e distances between C, D, and S in the retracted ded angle β between

ody coordinate system

t C can be derived by

3)

(5)

the body coordinate

oint C in the global

red according to the
 $-\sin \varphi \left| \begin{array}{cc} x_c \\ y_c \end{array} \right|_B$

(6)
 $\cos \varphi \left| \begin{array}{cc} y_c \\ y_c \end{array} \right|_B$

(7)
 sin $\varphi = \sqrt{1-\cos^2 \varphi}$ (4)

distances between *C*, *D*, and *S* in the retracted

ulic cylinders, the included angle β between

an be derived. In the body coordinate system

oordinates of joint point *C* can be derived sin $\varphi = \sqrt{1-\cos^2 \varphi}$ (4)

distances between *C*, *D*, and *S* in the retracted

ulic cylinders, the included angle β between

an be derived. In the body coordinate system

oordinates of joint point *C* can be derived distances between C, D, and S in the retracted
ulic cylinders, the included angle β between
an be derived. In the body coordinate system
oordinates of joint point C can be derived by
 β :
 $\begin{cases} x_c \\ y_c \end{cases} = -L_{CS} \begin{cases} \cos$ lic cylinders, the included angle β between
 y be derived. In the body coordinate system

ordinates of joint point *C* can be derived by
 β :
 $\begin{Bmatrix} x_c \\ y_c \end{Bmatrix}_B = -L_{cs} \begin{Bmatrix} \cos \beta \\ \sin \beta \end{Bmatrix}$ (5)

script "B" represe

$$
\begin{Bmatrix} x_C \\ y_C \end{Bmatrix}_{\text{B}} = -L_{CS} \begin{Bmatrix} \cos \beta \\ \sin \beta \end{Bmatrix}
$$
 (5)

owing L_{CS} , β :
 $\begin{cases} x_C \\ y_C \end{cases} = -L_{CS} \begin{cases} \cos \beta \\ \sin \beta \end{cases}$ (5)

here the subscript "B" represents the body coordinate

stem $x_B F y_B$.

Then, the coordinates of joint point *C* in the global

ordinate system xEy are d $\begin{cases} x_c \\ y_c \end{cases} = -L_{CS} \begin{cases} \cos \beta \\ \sin \beta \end{cases}$ (5)
where the subscript "B" represents the body coordinate
system $x_B F y_B$.
Then, the coordinates of joint point *C* in the global
coordinate system xEy are derived according to coordinates of joint point *C* in the global
tem xEy are derived according to the
formation equation:
 $\begin{cases} \n\sum_{G} \left\{ \int_{xF} \right\}_{G} + \left(\begin{array}{cc} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{array} \right) \left\{ \int_{y_C} \right\}_{B}$ (6)
the solight point *N* ca system $x_B r y_B$.

Then, the coordinates of joint point *C* in the global

coordinate system xEy are derived according to the

coordinate transformation equation:
 $\begin{cases} x_C \\ y_C \end{cases} = \begin{cases} x_F \\ y_F \end{cases} + \begin{pmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi &$

$$
\begin{Bmatrix} x_C \\ y_C \end{Bmatrix}_G = \begin{Bmatrix} x_F \\ y_F \end{Bmatrix}_G + \begin{pmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{pmatrix} \begin{Bmatrix} x_C \\ y_C \end{Bmatrix}_B \tag{6}
$$

$$
\begin{Bmatrix} x_N \\ y_N \end{Bmatrix}_{\text{G}} = \begin{Bmatrix} x_N \\ y_C - \sqrt{L_{NC}^2 - (x_C - x_N)^2} \end{Bmatrix}
$$
 (7)

Then, the coordinates of Joint point C in the
coordinate system xEy are derived according
coordinate transformation equation:
 $\begin{cases} x_C \\ y_C \end{cases} = \begin{cases} x_F \\ y_F \end{cases} + \begin{pmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{pmatrix} \begin{cases} x_C \\ y_C \end{cases}$
The coor ordinate system xzy are derived according to the
ordinate transformation equation:
 $\begin{cases} x_c \\ y_c \end{cases} = \begin{cases} x_F \\ y_F \end{cases} + \begin{pmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{pmatrix} \begin{cases} x_c \\ y_c \end{cases}$ (6)
The coordinates of joint point *N* can be obtai coordinate transformation equation:
 $\begin{Bmatrix} x_c \\ y_c \end{Bmatrix}_G = \begin{Bmatrix} x_F \\ y_F \end{Bmatrix}_G + \begin{Bmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{Bmatrix} \begin{Bmatrix} x_c \\ y_c \end{Bmatrix}_B$ (6)

The coordinates of joint point *N* can be obtained according

to the Pythagorean The $\begin{cases} x_c \\ y_c \end{cases} = \begin{cases} x_F \\ y_F \end{cases} + \begin{pmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{pmatrix} \begin{cases} x_c \\ y_c \end{cases}$ (6)
The coordinates of joint point *N* can be obtained according
to the Pythagorean Theorem:
 $\begin{cases} x_N \\ y_N \end{cases} = \begin{cases} x_N \\ y_c - \sqrt{L_{xc}^2 - (x_C \left\{\mathbf{y}_c\right\}_{G} = \left\{\mathbf{y}_F\right\}_{G} + \left\{\sin\varphi \cos\varphi\right\}$
The coordinates of joint point *N* can be of
to the Pythagorean Theorem:
 $\left\{\mathbf{x}_N\right\}_{G} = \left\{\mathbf{x}_r - \sqrt{L_{NC}^2 - (x_C - \mathbf{w})} \right\}$
where \mathbf{x}_N is a constant, because th Indianates of Joint point *N* can be obtained according
agorean Theorem:
 $\begin{cases} x_N \\ y_N \end{cases} = \begin{cases} x_N \\ y_C - \sqrt{L_{NC}^2 - (x_C - x_N)^2} \end{cases}$ (7)
is a constant, because the hydraulic cylinder *MN*
nove horizontally.
-7) were explicitly

 $\begin{Bmatrix} x_N \\ y_N \end{Bmatrix}_{\text{G}} = \begin{Bmatrix} x_N \\ y_C - \sqrt{L_{NC}^2 - (x_C - x_N)^2} \end{Bmatrix}$ (7)

nere x_N is a constant, because the hydraulic cylinder *MN*

n only move horizontally.

Eqs. (1-7) were explicitly formulated, allowing for the

ect det $\begin{cases} x_N \\ y_N \end{cases} = \begin{cases} x_N \\ y_C - \sqrt{L_{NC}^2 - (x_C - x_N)^2} \end{cases}$
where x_N is a constant, because the hydraulic cylinder
can only move horizontally.
Eqs. (1-7) were explicitly formulated, allowing for
direct determination of the ge $\left[\frac{N_N}{N_C^2 - (x_C - x_N)^2}\right]$ (7)

e the hydraulic cylinder *MN*

ormulated, allowing for the

cometric coordinates of the

the equations or calculating
 $\frac{N}{NNAMIC}$ ANALYSIS

ic mechanical equilibrium

driving the thigh *E* $(V_N)_G$ $[Y_C - \sqrt{L_{NC}} - (x_C - x_N)^2]$
where x_N is a constant, because the hydraulic cylinder MN
can only move horizontally.
Eqs. (1-7) were explicitly formulated, allowing for the
direct determination of the geometric coordinat where x_N is a constant, because the hydraulic cylinder *MN*
can only move horizontally.
Eqs. (1-7) were explicitly formulated, allowing for the
direct determination of the geometric coordinates of the
specified points,

IAENG International Journal of Applied Mathemati
CS as a whole, the moment equilibrium equation was cylinder extended within its established for point *E*, and the force F_{CS} could be obtained swing angle θ of th **EXECU INTENTE INTERT IN SUMMANUE ATTACK CONSTRESS AND SUMMANUE CONSTRESS AND SUMMANUE SETABLISHED (S) as:**

F_{CS} = $\frac{M_E}{\sqrt{E C \times n_{CS} \cdot \frac{M_E}{dL}}}$ (8) 3) Anti-interference required as:

$$
F_{CS} = -\frac{M_E}{\left\| \mathbf{EC} \times \mathbf{n}_{CS} \right\|_2}
$$
 (8) (3) Anti-interference requirements

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moment equilibrium equation was cylinder

and the force F_{CS} could be obtained swing ang
 $= -\frac{M_E}{\|EC \times n_{CS}\|_2}$ (8) 3) Anti-in

le magnitude of the driving moment a) To p

bint E (**ECALCO International Journal of Applied Mathematic

ent equilibrium equation was cylinder extended within its s

the force** F_{CS} **could be obtained swing angle** θ **of the thigh shoul
** $\frac{d\theta}{dL_{MN}}$ **
 \mathbf{EC} \times \mathbf{n}_{CS} ||_2** where M_E indicates the magnitude of the driving moment **IAENG International Journal of Applied Mathen**
hole, the moment equilibrium equation was cylinder extended within
or point E, and the force F_{CS} could be obtained swing angle θ of the thigh
 $F_{CS} = -\frac{M_E}{\| \mathbf{EC} \times \math$ **IAENG International Journal of Applied Mathematio**

CS as a whole, the moment equilibrium equation was cylinder extended within its is

established for point *E*, and the force F_{CS} could be obtained swing angle θ o ECS as a whole, the moment equilibrium equation was cylinder extended within its spertablished for point *E*, and the force F_{CS} could be obtained swing angle θ of the thigh should as:
 $F_{CS} = -\frac{M_E}{\|E C \times n_{CS}\|_2}$ (CS as a whole, the moment equilibrium equation was cylinder extended with
established for point *E*, and the force F_{CS} could be obtained swing angle θ of the thig
as:
 $F_{CS} = -\frac{M_E}{\| \mathbf{EC} \times \mathbf{n}_{CS} \|_2}$ (8) 3) Anti-CS as a whole, the moment equilibrium equation was cylinder extended within in established for point *E*, and the force F_{CS} could be obtained swing angle θ of the thigh since $\frac{dE}{dL_h}$.

Where M_E indicates the ss:
 $F_{CS} = -\frac{M_E}{\| \mathbf{EC} \times \mathbf{n}_{CS} \|_2}$ (8) 3) Anti-interference required to the joint point *E* (along the z-axis direction);

applied to the joint point *E* (along the z-axis direction);

all To prevent the move the si established to the joint external to solve the reaction force *F*_{*NC*} on the hydraulic extending the reaction $F_{Nc} = -\frac{\left|F_{CS} \times CD\right|_2}{\left\|ND \times N_{Nc}\right\|_2}$ (9)

Force $\frac{m}{N}$ and $\frac{m}{N}$ on the sliding sleeve of the **IAENG International Journal of Ap**

moment equilibrium equation was cylinder

and the force F_{CS} could be obtained swing any
 $= -\frac{M_E}{\|EC \times n_{CS}\|_2}$ (8) 3) Anti-in

ne magnitude of the driving moment a) To I

int E (a *NC F CD* the force *F_{CS}* could be obtained within its some that the force *F_{CS}* could be obtained swing angle *θ* of the thigh shoul d*H_{LMS}*
 N_{EC} × *N_{CS}* |₂ (8) 3) Anti-interference requirement and *H_{LMS}* > (8) 3 Where **CD** and *ND* are the direction vectors of the force on the set of the force of the force of the force of the force of the moment at point *E* generated by *Fcs*; and *n*_{cs} is $\delta \leq \delta_{\text{max}}$.

When the unit direc applied to the joint point *E* (along the z-axis direction); the sliding slice of the means of the vector; " \times " interfering, the rotation and η " \parallel \parallel_2 " denotes the Euclidean norm of the vector; " \times " the hydr

cylinder:

$$
F_{NC} = -\frac{\left\|F_{cs} \times CD\right\|_2}{\left\|ND \times n_{NC}\right\|_2}
$$
 (9)

CD and *CD*.
 CD and *CD* an represent the moment apoint of the moment and to material experiment and the unit direction vector of F_{CS} . Subsequently, taking the mechanism *DNCS* as a unified in included angle α between *ES* subsequently, taking vector of the moment at point *E* generated by Fcs ;
the unit direction vector of Fcs .
Subsequently, taking the mechanism *DNCS* as
system, the moment equilibrium equation at po
established to solve the reaction force F Finally, taking the mechanism *DNCS* as a unified

Subsequently, taking the output force *F_{<i>NC*} on the hydraulic

stem, the moment equilibrium equation at point *D* was

and linder:

linder:
 $F_{\gamma C} = -\frac{\left\|F_{CS} \times CD\right\|$ eylinder:
 $F_{NC} = -\frac{\left\|F_{CS} \times CD\right\|_2}{\left\|ND \times n_{NC}\right\|_2}$ (9)

where **CD** and *ND* are the direction vectors of the pendulum following requirement should

CD and the connecting rod *ND*, respectively; and n_{NC} interferen *F_{NC}* = $-\frac{\left\|F_{CS} \times CD\right\|_2}{\left\|ND \times n_{NC}\right\|_2}$ (9)

where **CD** and *ND* are the direction vectors of the pendulum following *r*

CD and the connecting rod *ND*, respectively; and n_{NC} interference

represents the uni *A. Design variables*
 A. Design variables the profilement of the force onnecting rod *ND*, respectively;
 A. Finally, the output force F_{MN} of the hydraulic cyl

was obtained:
 $F_{MN} = F_{NC} \cos \delta$

where δ refers to

$$
F_{MN} = F_{NC} \cos \delta \tag{10}
$$

Function vector of the force on the interaction and to maintain a safety dis-

needing rod NC.

Interaction vector of the force on the and to maintain a safety dis-

meeting rod NC.

Interaction vector of the force on the represents the unit direction vector of the force on the and o manufar accounting rod NC.

Finally, the output force F_{MN} of the hydraulic cylinder MN

was obtained:
 $F_{MN} = F_{NC} \cos \delta$ (10) represents the direction vector connecting roa *NC*.

Was obtained:

Was obtained:

Was obtained:

Was obtained:

Was obtained:
 $F_{MN} = F_{NC} \cos \delta$ (10) represents the direction vector

where *DE* denotes the position of the inequality is the vertic

CN to Finally, the output force F_{MN} of the hydraulic cylinder MN

where *DE* denotes the position

where D are extrical

where δ refers to the rotation angle from the connecting rod

of the inequality is the vertical
 was obtained:

where DE denotes the

where δ refers to the rotation angle from the connecting rod

convention angle from the connecting rod of the inequality is the

CN to the hydraulic cylinder MN.

V. INTEGRATED LEG $F_{MN} = F_{NC} \cos \delta$ (10) represents the direction vec

CN to the hydraulic cylinder MN.

CN to the hydraulic cylinder MN.

V. INTEGRATED LEG OPTIMIZATION MODEL and r_E is the radius of the

4. Design variables

By changing t **ND** are the direction vectors of the pendulum following requirement should be encompacting red MD, respectively; and n_{χ} interference between the pendulum CD, L_CD and χ is the time of the force on the and *V.* INTEGRATED LEG OPTIMIZATION MODEL
A. Design variables
By changing the configuration of the thigh
mechanism to reduce the peak force of the hydraulic *CMN*. This involved altering the horizontal coordinate
point *N* V. INTEGRATED LEG OPTIMIZATION MODEL and r_E is the radius of the beari

Design variables

d) To avoid interference with

By changing the configuration of the thigh linkage

cchanism to reduce the peak force of the hydra *A. Design variables*
 MY changing the configuration of the thigh linkage

mechanism to reduce the peak force of the hydraulic cylinder
 MN. This involved altering the horizontal coordinate of joint

point *N*, as wel mechanism to reduce the peak force of the hydraulic cy *MN*. This involved altering the horizontal coordinate o
point *N*, as well as the horizontal and vertical coordinate o
point points *C*, *D*, and *F*. They served as MN. This involved altering the horizontal coordinate of joint
point N, as well as the horizontal and vertical coordinates of
joint points C, D, and F. They served as the design variables.
In this case, the design variable

$$
\mathbf{x} = \{y_N, x_C, y_C, x_D, y_D, x_F, y_F\}^{\text{T}}
$$
 (11)

$$
f(x) = \max(F_{MN})
$$
 (12)

installation. For *N* and *NC* determined by the size of the bydraulic cylinder *MN* in the working range.
 $f(x) = \max(F_{MN})$ (12) During the robothigh *EFI* and the simulated and 1

1) Lower bound of rod length simulated and 1

The rod *NC* 2) Monotonicity of mechanism motion

2) Monotonicity of the Monotonic step of the parameterism of rod length

2) Lower bound of rod length

2) The rod NC should be designed to incorporate a
 $\theta \in [8$

single-axis force se *C. Constraint conditions*

ingh *EF1* and the divergence incorporate simulated and measure

increased swing that its length while $\theta \in [8^{\circ}, 5^{\circ}]$ for the

single-axis force sensor, ensuring that its length while $\theta \in$

$$
L_{NC} \ge L_{\min} \tag{13}
$$

al of Applied Mathematics

cylinder extended within its specified working range, the

swing angle θ of the thigh should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14) **al of Applied Mathematics**
cylinder extended within its specified working range, the
swing angle θ of the thigh should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14)
3) Anti-interference requirements

$$
\frac{\mathrm{d}\theta}{\mathrm{d}L_{\scriptscriptstyle MN}}>0\tag{14}
$$

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cylinder extended within its specified working range, the

swing angle θ of the thigh should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14

3) Anti-interference requirements

a) To prevent of Applied Mathematics

linder extended within its specified working range, the

ing angle θ of the thigh should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14)

Anti-interference requirements

a) To prevent the movemen **al of Applied Mathematics**

cylinder extended within its specified working range, the

swing angle θ of the thigh should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14)

3) Anti-interference requirements

a) To prevent t **isomage 3**
 isomage 10 C to the connection angle θ of the thigh should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14)

3) Anti-interference requirements

a) To prevent the movement of the connecting rod *NC* and
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cylinder extended within its specified working range, the

swing angle θ of the thigh should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14)

3) Anti-interference requirements

a) To prevent **al of Applied Mathematics**

eylinder extended within its specified working range, the

swing angle θ of the thigh should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14)

3) Anti-interference requirements

a) To prevent linder extended within its specified working range, the

ing angle θ of the thigh should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14)

Anti-interference requirements

a) To prevent the movement of the connecting rod

$$
\delta \le \delta_{\max} \tag{15}
$$

swing angle θ of the thigh should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14)

3) Anti-interference requirements

a) To prevent the movement of the connecting rod *NC* and

the sliding sleeve of the hydraulic cylind $\frac{d\theta}{dL_{MN}} > 0$ (14)

3) Anti-interference requirements

a) To prevent the movement of the connecting rod *NC* and

the sliding sleeve of the hydraulic cylinder *MN* from

interfering, the rotation angle δ of the con 3) Anti-interference requirements

a) To prevent the movement of the connecting rod NC and

the sliding sleeve of the hydraulic cylinder MN from

interfering, the rotation angle δ of the connecting rod NC to

the hydra 3) Anti-interference requirements

a) To prevent the movement of the connecting rod NC and

the sliding sleeve of the hydraulic cylinder MN from

interfering, the rotation angle δ of the connecting rod NC to

the hydra **matics**

in its specified working range, the

h should consistently increase.
 $\frac{d\theta}{dL_{MN}} > 0$ (14)

irements

ement of the connecting rod *NC* and

the hydraulic cylinder *MN* from

ngle δ of the connecting rod *NC* Example the interact of the hydraulic cylinder MN from
erfering, the rotation angle δ of the connecting rod NC to
by hydraulic cylinder MN should not exceed the maximum
missible value δ_{max} .
 $\delta \leq \delta_{max}$ (15)
b) A intertering, the rotation angle δ of the connecting rod *NC* to
the hydraulic cylinder *MN* should not exceed the maximum
permissible value δ_{max} . $\delta \leq \delta_{\text{max}}$ (15)
b) A bearing should be installed at point *F* the hydraulic cylinder *MN* should not exceed the maximum

permissible value δ_{max} . (15)

b) A bearing should be installed at point *F*, and the

included angle α between *ES* and *EI* should be maintained

not le $\frac{d\theta}{dL_{MN}} > 0$ (14)

requirements

movement of the connecting rod *NC* and

of the hydraulic cylinder *MN* from

on angle δ of the connecting rod *NC* to
 rMN should not exceed the maximum
 $\delta \leq \delta_{\text{max}}$ (15)

u dL_{MN}

The movement of the connecting rod *NC* and

eve of the hydraulic cylinder *MN* from

cotation angle δ of the connecting rod *NC* to

cotation angle δ of the connecting rod *NC* to
 δ_{max} .
 $\delta \leq \delta_{\text$

$$
\alpha \ge \alpha_{\min} \tag{16}
$$

c) As the thigh *EFI* moved within the working range, the

$$
\frac{\|\bm{DE} \times \bm{DC}\|_2}{L_{CD}} \ge \frac{1}{2} w_{CD} + r_E + d \tag{17}
$$

included angle α between *ES* and *EI* should be maintained
not less than the minimum permissible value α_{min} to prevent
interference with the installation space and the internal
mechanism layout within the thigh.
 $\$ not less than the minimum permissible value α_{min} to prevent
interference with the installation space and the internal
mechanism layout within the thigh.
 $\alpha \ge \alpha_{min}$ (16)
c) As the thigh *EFI* moved within the working r interference with the installation space and the internal
mechanism layout within the thigh.
 $\alpha \ge \alpha_{min}$ (16)

c) As the thigh *EFI* moved within the working range, the

following requirement should be emphasized to prev mechanism layout within the thigh.
 $\alpha \ge \alpha_{min}$ (16)

c) As the thigh *EFI* moved within the working range, the

following requirement should be emphasized to prevent

interference between the pendulum *CD* and the joint $\alpha \ge \alpha_{min}$ (16)

c) As the thigh *EFI* moved within the working range, the

following requirement should be emphasized to prevent

interference between the pendulum *CD* and the joint point *E*,

and to maintain a safety c) As the thigh *EFI* moved within the working range, the following requirement should be emphasized to prevent interference between the pendulum *CD* and the joint point *E*, and to maintain a safety distance *d*:

<u> $\left|$ interference between the pendulum *CD* and the joint point *E*,

and to maintain a safety distance *d*:
 $\frac{\|\textbf{DE} \times \textbf{DC}\|_2}{L_{CD}} \ge \frac{1}{2} w_{CD} + r_E + d$ (17)

where *DE* denotes the position vector of *DE*, and *DC*

repr interference with the installation space and the internal
mechanism layout within the thigh.
 $\alpha \ge \alpha_{min}$ (16)
c) As the thigh *EFI* moved within the working range, the
following requirement should be emphasized to prevent L_{CD} 2 D^2 L^2 L^2 L^2 L^2 L^2 L^2 L^2 L^2 or D^2 respects the direction vector of pendulum *CD*. The left side the inequality is the vertical distance between the joint int *E* and the pendulum *CD* where *DE* denotes the position vector of *DE*, and *DC*
represents the direction vector of pendulum *CD*. The left side
of the inequality is the vertical distance between the joint
point *E* and the pendulum *CD*. *Lcp* represents the direction vector of pendulum *CD*. The left side
of the inequality is the vertical distance between the joint
point *E* and the pendulum *CD*. *L*_{*CD*} refers to the length of the
pendulum *CD*;
and r_E i interference between the pendulum *CD* and the joint pint.

interference between the pendulum *CD* and the joint point *E*,

and to maintain a safety distance *d*:

<u>lex</u> > L_{CO}
 $\geq \frac{1}{2} w_{CO} + r_E + d$ (17)

where *DE*

$$
L_{ME} \le L_{ME}^{\text{max}} \tag{18}
$$

between points D and E is greater than the sum of their respective radii to properly accommodate these components. of the inequality is the vertical distance between the joint
point *E* and the pendulum *CD*. *LcD* refers to the length of the
pendulum *CD*;
and r_E is the radius of the bearing at point *E*.
d) To avoid interference w erference with the rest of the machine, the
ce between points M and E should be
installation and operation.
 $L_{ME} \leq L_{ME}^{\text{max}}$ (18)
Prequires the installation of a joint bearing,
should be furnished with a dynamic sealin rizontal distance between points *M* and *E* should be
ntrolled during installation and operation.
 $L_{ME} \leq L_{ME}^{max}$ (18)
e) Joint point *D* requires the installation of a joint bearing,
d joint point *E* should be furnis

$$
L_{ED}^{\min} \ge r_D + r_E \tag{19}
$$

 $F_{MN} = F_{NC} \cos \delta$ (10) represents the direction vector of percosition
represents the direction vector of percosition angle from the connecting rod
pint *E* and the inequality is the vertical disposition
republime CD, W_{CD} Int N, as well as the horizontal and vertical coordinates of

Int point D requires the inst

Int points C, D, and F. They served as the design variables.

this case, the design variables could be expressed as:
 $x = \{y_N, x_C$ Signifyoms C, D, and F. They served as the design variables, and joint point E should be the

In this case, the design variables could be expressed as:
 $x = \{y_x, x_c, y_c, x_p, y_p, x_F, y_F\}^\top$ (11) between points D and E is
 $x = \{$ accommodated the necessary space for the sensor's the final values of the divergend the necessary space for the single-axis force sensor, ensuring that its length where L_{min} respective function L'_j .

The objective fun Configuration of the thigh linkage

incontrolled during installation

impediator equal coordinates of joint controlled during installation
 L,

incrizontal and vertical coordinates of e) Joint point *D* requires

C. T *Let the constraint condition*

The objective function was defined as the peak force of the

hydraulic cylinder *MN* in the working range.
 L (12) During the robot's was

thigh *EFI* and the drive

The rod *NC* should b For precise control of the hydraulic cylinder with an interpolation of For precise control of the hydraulic cylinder MN must be monotonic. This indicated that as the diversion of the smoothnical sine and measured for $U_{\$ 1) Lower bound of rod length

The rod *NC* should be designed to incorporate a

simulated and measured for

single-axis force sensor, ensuring that its length while $\theta \in [55^{\circ}, 64^{\circ}]$ when climb

accommodated the necess controlled during installation and operation.
 $L_{ME} \leq L_{MK}^{max}$ (18)

e) Joint point *D* requires the installation of a joint bearing,

and joint point *E* should be furnished with a dynamic sealing

structure. Hence, i tion. (18)

ion of a joint bearing,

ith a dynamic sealing

ure that the distance

nan the sum of their

te these components.

(19)

(39)

SISS

e swing angle θ of the

at joint point E were

operating condition.
 $L_{ME} \leq L_{ME}^{max}$ (18)

e) Joint point *D* requires the installation of a joint bearing,

and joint point *E* should be furnished with a dynamic sealing

structure. Hence, it is essential to ensure that the distance

betwe point *E* and the pendulum *CD*. *Lcp* refers to the length of the pendulum *CD*; w_{CD} denotes the width of the pendulum *CD*; w_{CD} denotes the width of the pendulum *CD*; $\frac{1}{N}$ is the radius of the bearing at poi *PCRICO COMATRALT CON* W_{CD} denotes the wheat r_E is the radius of the bearing at point *E.* (*I* or avoid interference with the rest of the machine, the horizontal distance between points *M* and *E* should be contro between points *D* and *E* is greater than the sum of their
respective radii to properly accommodate these components.
 $L_{ED}^{min} \ge r_D + r_E$ (19)
VI. EXAMPLE ANALYSIS
During the robot's walking motion, the swing angle θ of respective radii to properly accommodate these components.
 $L_{ED}^{min} \ge r_D + r_E$ (19)

VI. EXAMPLE ANALYSIS

During the robot's walking motion, the swing angle θ of the

thigh *EFI* and the drive moment M_E at joint point *L*_{*ED}* are *F* and *E F P* and *E F F E F B P E F B B EFI* and the drive moment *M_E* at joint point *E* were simulated and measured for each operating condition. $\theta \in [8^\circ, 55^\circ]$ for the r</sub> controlled during installation and operation.
 $L_{ME} \leq L_{ME}^{max}$ (18)

e) Joint point *D* requires the installation of a joint bearing,

and joint point *E* should be furnished with a dynamic sealing

structure. Hence, it VI. EXAMPLE ANALYSIS
During the robot's walking motion, the swing angle θ of the
gh *EFI* and the drive moment M_E at joint point *E* were
nulated and measured for each operating condition.
 \in [8°,55°] for the robot During the robot's walking motion, the swing angle θ of the thigh *EFI* and the drive moment M_E at joint point *E* were simulated and measured for each operating condition. $\theta \in [8^\circ, 55^\circ]$ for the robot walking on During the robots waiking motion, the swing angle *θ* of the thigh *EFI* and the drive moment M_E at joint point *E* were simulated and measured for each operating condition. $\theta \in [8^\circ, 55^\circ]$ for the robot walking on f

Example 19
 $\frac{1}{2}$
 $\frac{1}{2}$ **EXECUTE:**
 $\frac{1}{25}$
 $\frac{1}{20}$
 $\frac{1$ **EVALUATE:**
 EVALUATE:
 $\frac{D}{E}$ (0, (10)
 EVALUATE:

Fig. 5 Driving moment at joint point E

Fig. 6 presents the magnitude of the force of the hydraulic

cylinder MN. At a swing angle θ of 58°, the hydraulic

eva conditions.

2 15 7 70 450 33 d 0 d 33 **s.t.** *MN NCME EDMN CD L L L L L DE DC* where the rotation angle does not exceed 15°; the included angle should be kept as least 7°; the length of the

 $\begin{vmatrix}\n\alpha \ge 7'\\
L_{NC} \ge 70 \\
L_{M} \le 450\n\end{vmatrix}$ $L_{KL} \le 450$ $L_{ED} \ge 33$ $\frac{d\theta}{dL_{MN}} > 0$ $\frac{dE}{dL_{MN}} > 0$ $\frac{dE}{dL_{MN}} > 0$ $\frac{dE}{dL_{MN}} > 0$ $\frac{dE}{dL_{MN}} > 0$ $\frac{dE}{dL_{CD}} > 33$ Thigh sweet the rotation angle δ does not e $L_{\text{MC}} \geq 70$ (20) $\frac{3.6000}{5.6000}$ $\frac{1}{20}$ 40
 $L_{\text{ED}} \geq 33$
 $\frac{d\theta}{dL_{\text{MN}}} > 0$ Fig. 8 Comparison of hydraulic eylind
 $\frac{d\theta}{dL_{\text{MN}}} > 0$ Fig. 8 Comparison of hydraulic eylind
 $\frac{d\theta}{dL_{\text{MN}}} > 0$ Fig. 8 $L_{BE} \ge 450$
 $L_{ED} \ge 33$
 $L_{BD} \ge 33$
 $\frac{d\theta}{dL_{MN}} > 0$
 $\frac{dDEx}{DCD} \ge 33$

Where the rotation angle δ does not exceed 15°; the included

angle α should be kept as least 7°; the length of the Maximum AND OPTIMIZED **EXECUTE 19 AND COLUTE AND COLUTE AND COLUTE AND COLUTE AND COLUTE (THE HYDRAL Where the rotation angle** δ **does not exceed 15°; the included angle** α **should be kept as least 7°; the length of the connecting rod** *NC* **s** $L_{ED} \geq 33$
 $\frac{d\theta}{dL_{MN}} > 0$
 $\frac{d\theta}{dL_{MN}} > 0$

where the rotation angle δ does not exceed

angle α should be kept as least 7°;

connecting rod *NC* should be no less

distance of *ME* is no more than 450 mm;

i $\frac{d\theta}{dL_{MN}} > 0$
 $\frac{dE}{dL_{MN}} > 0$
 $\frac{dE}{dL_{CD}} \ge 33$

here the rotation angle δ does not exceed 15°; the included obegine

meeting rod *NC* should be no less than 70 mm; the three same of *ME* is no more than 450 mm Where the rotation angle δ does not exceed 15°; the included
angle α should be kept as least 7°; the length of the connecting rod *NC* should be no less than 70 mm; the distance of *ME* is no more than 450 mm; the d **IDE** \times DCI₂ \geq 33

Where the rotation angle δ does not exceed 15°; the included

angle α should be kept as least 7°; the length of the

connecting rod NC should be no less than 70 mm; the

distance of ME is where the rotation angle δ does not exceed 15°; the angle α should be kept as least 7°; the leng connecting rod *NC* should be no less than 70 distance of *ME* is no more than 450 mm; the distance be pendulum rod *C*

	al of Applied Mathematics	
	TABLE I	
		COORDINATES OF POINTS OF THE ORIGINAL AND OPTIMIZED THIGH LINKAGE
	MECHANISM	
		Optimized/mm
	Original/mm	
\overline{M}	$(40, -442)$	$(40, -448)$
\boldsymbol{N}		
C	$(40, -149)$	$(40, -136)$
D	$(70, -32)$	$(66, -37)$
Joint points E	$(-10, -40)$	$(-23, -48)$
\overline{F}	(0, 0) (39, 31)	(0, 0) (58, 32)

configuration
M', N', C', D', E, S', I' -coordinates of joint points of the optimized

explined a reduction of the extreme working M, N, C, D, E, S, I - coordinates of joint points

and the extreme working M, N, C, D, E, S, I - coordinates of joint points
 M, N, C, D, E, S, I - coordinates of joint
 M, N, C, D, E, S, I - c *f x F* M. N, C, D, E, S, I - coordinates of joint points of the original mechanism

M', N', C', D', E, S', I - coordinates of joint points of the original mechanism

M', N', C', D', E, S', I' - coordinates of joint points of the *the M.N.C, D, E, S, I* - coordinates of joint points of the original mechanism
 M', N', C', D', E, S', I - coordinates of joint points of the original mechanism
 M', N', C', D', E, S', I - coordinates of joint points M. N, C, D, E, S, I - coordinates of joint points of the original mechanism
configuration
M', N', C', D', E, S', I' - coordinates of joint points of the optimized
mechanism configuration
Fig. 7 Original and optimized mech *M, N, C, D, E, S, I* - coordinates of joint points of the original mechanism
 M', N', C', D', E, S', I' - coordinates of joint points of the optimized

mechanism configuration

Fig. 7 Original and optimized mechanism c f joint points of the original mechanism
iguration
interests of joint points of the optimized
n configuration
ized mechanism configuration
comparison curves of hydraulic
the original and optimized
duction in both the maxi *M, N, C, D, E, S, I* - coordinates of joint points of the original mechanism
 M', N', C', D', E, S', I' - coordinates of joint points of the optimized

mechanism configuration

Fig. 7 Original and optimized mechanism c nanism

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L. II *M, N, C, D, E, S, I* - coordinates of joint points of the original mechanism
 M', N', C', D', E, S', I' - coordinates of joint points of the optimized

mechanism configuration

Fig. 7 Original and optimized mechanism c *M', N', C', D', E, S', I'* - coordinates of joint points of the optimized
mechanism configuration
Fig. 7 Original and optimized mechanism configuration
As depicted in Fig. 8, the comparison curves of hydraulic
cylinder f mechanism configuration

Fig. 7 Original and optimized mechanism configuration

As depicted in Fig. 8, the comparison curves of hydraulic

cylinder force between the original and optimized

mechanism presented a reduction Fig. 7 Original and optimized mechanism configuration
As depicted in Fig. 8, the comparison curves of hydraulic
cylinder force between the original and optimized
mechanisms presented a reduction in both the maximum
thrust

Fig. 8 Comparison of hydraulic cylinder forces of the original and optimized mechanism

	20	40	60 80	100
			Thigh swing angle θ /°	
		mechanism	Fig. 8 Comparison of hydraulic cylinder forces of the original and optimized	
		TABLE II		
			PEAK OUTPUT FORCE OF THE HYDRAULIC CYLINDER MN OF THE ORIGINAL AND OPTIMIZED MECHANISM	
	Original/N		Optimized/N	Reduced percentage
Maximum thrust force	8383.9		7061.2	15.78%
Maximum pulling force	6592.9		5542.3	15.94%
VII. VALIDATION OF OPTIMIZATION EFFECTS BASED ON				
		EXPERIMENT	Herein, a suspended swing experiment on the integrated	

EXPERIMENT

IAENG International Journal of Applied Mathemat
model by comparing the measured hydraulic cylinder force
with the calculated hydraulic cylinder force from the
integrated leg kinematic model. The strain electrical
measureme IAENG International Journal of Applied Mathematic
model by comparing the measured hydraulic cylinder force
with the calculated hydraulic cylinder force from the
integrated leg kinematic model. The strain electrical
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model by comparing the measured hydraulic cylinder force

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integrated leg kinematic model. The strain electrical

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model by comparing the measured hydraulic cylinder force

with the calculated hydraulic cylinder force from the

integrated leg kinematic model. The strain electrical

measur **Stress International Journal of Applied Mathemation**

stress distribution and verify whether the leg mechanism can

the calculated hydraulic cylinder force from the

integrated leg kinematic model. The strain electrical
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model by comparing the measured hydraulic cylinder f

with the calculated hydraulic cylinder force from

integrated leg kinematic model. The strain elect

measurement was conducted on key parts to ob **IAENG International Journal of Applied**

model by comparing the measured hydraulic cylinder force

with the calculated hydraulic cylinder force from the

integrated leg kinematic model. The strain electrical

measurement IAENG International Journal of Applied Mathema

and the calculated hydraulic cylinder force

the calculated hydraulic cylinder force from the

egrated leg kinematic model. The strain electrical

assurement was conducted on IAENG International Journal of Applied Mathem

model by comparing the measured hydraulic cylinder force

with the calculated hydraulic cylinder force from the

integrated leg inclusion conducted on key parts to obtain the

slide rail, and the integrated leg mechanism. The single rangest and the integrated leg kinematic model. The strain electrical measurement was conducted on key parts to obtain the actual stress distribution and verify whet model by comparing the measured hydraulic cylinder force
with the calculated hydraulic cylinder force from the
integrated leg kinematic model. The strain electrical
measurement was conducted on key parts to obtain the actu model by comparing the measured hydraulic cylinder force
with the calculated hydraulic cylinder force from the
integrated leg kinematic model. The strain electrical
measurement was conducted on key parts to obtain the actu with the calculated hydraulic cylinder force from the
integrated leg kinematic model. The strain electrical
measurement was conducted on key parts to obtain the actual
stress distribution and verify whether the leg mechani integrated leg kinematic model. The strain electrical
measurement was conducted on key parts to obtain the actual
stress distribution and verify whether the leg mechanism can
meet the strength requirements.
A. Platform of mechanism.

Fig. 10 The motion conditions

Force sensor was the ground hydraulic station, which provided a

Force sensor was installed at the connecting rod *CS*. In this

platform was used on the connecting rod *CS*. In this

the int **Example 19**
 Case, the operation of the single leg experimental platform
 Case of the single leg experimental
 Case of the single leg experimental
 Case of 18
 Case of 18
 Case of 18
 Case of 18
 Case of 1 Example 1

Fig. 9 Single leg experimental platform

The power mechanism of the single leg experimental

platform was the ground hydraulic station, which provided a

maximum hydraulic cylinder force of 18 MPa and a

maxi Fig. 9 Single leg experimental platform
The power mechanism of the single leg experimental
platform was the ground hydraulic station, which provided a
maximum hydraulic cylinder force of 18 MPa and a
maximum stroke of 72 m Fig. 9 Single leg experimental platform
The power mechanism of the single leg experimental
platform was the ground hydraulic station, which provided a
maximum hydraulic cylinder force of 18 MPa and a
maximum stroke of 72 m The power mechanism of the single leg experimental

atform was the ground hydraulic station, which provided a

ximum stroke of 72 mm.

In the integrated leg mechanism, the thigh hydraulic

conditions integrated using a di Platform was the ground hydraulic station, which provided a
maximum hydraulic cylinder force of 18 MPa and a
maximum stroke of 72 mm.
In the integrated using a displacement sensor, and a
row is installed at the connecting

maximum hydraulic cylinder force of 18 MPa and a

maximum stroke of 72 mm.

In the integrated leg mechanism, the thigh hydraulic

cylinder was integrated using a displacement sensor, and a

force sensor was installed at t maximum stroke of 72 mm.

In the integrated leg mechanism, the thigh hydraulic

cylinder was integrated using a displacement sensor, and a

frig. 11 Experimental data of thigh

force sensor was installed at the connecting In the integrated leg mechanism, the thigh hydraulic

cylinder was integrated using a displacement sensor, and a

force sensor was installed at the connecting rod CS. In this

case, the operating parameters of the thigh c explinder was integrated using a displacement sensor, and a

endurance of Eq. 11 Experimental data of thigh

force sensor was installed at the connecting rod CS. In this

case, the operating parameters of the thigh cylind Force sensor was installed at the connecting rod CS. In this

case, the operating parameters of the thigh cylinder could be

better measured. A single-axis force sensor model M3624A $\frac{\text{FokCE COMP}}{\text{high joint}}$

was used on the co case, the operating parameters of the thigh cylinder could be

better measured. A single-axis force sensor model M3624A was used on the connecting rod CS.

Massured fore was used on the connecting rod CS.

B. The suspende better measured. A single-axis force sensor model M3624A Force compassion of was used on the connecting rod CS.

Was used on the connecting rod CS.

B. The suspened swing experiment 15.0° 43.7

The motion conditions of th performed. The suspened swing experiment

The motion conditions of thigh suspended swing were set

the motion conditions of thigh suspended swing were set

geths of the thigh and calf cylinders, and the dwell time. As

use and the d B. The suspened swing experiment

The motion conditions of thigh suspended swing were set

up, encompassing parameters like running velocity, the

lengths of the thigh and calf cylinders, and the dwell time. As

shown in The motion conditions of thigh suspended swing were set 35.0° 105.5

up, encompassing parameters like running velocity, the

lengths of the thigh indicalf cylinders, and the dwell time. As

shown in Fig. 10, the thig up, encompassing parameters like running velocity, the

lengths of the thigh and calf cylinders, and the dwell time. As

shown in Fig. 10, the thigh swing condition facilitated to

endurance of 2 seconds when the shigh joi lengths of the thigh and calf cylinders, and the dwell time. As

shown in Fig. 10, the thigh swing condition facilitated to

endurance of 2 seconds when the thigh joint angle shifted to

15°, 35°, 55°, 75°, 85°, and 90°,

shown in Fig. 10, the thigh swing condition facilitated to
maintain the shank joint angle at 54.6°, and to ensure the
endurance of 2 seconds when the thigh joint angle shifted to
15°, 35°, 55°, 75°, 85°, and 90°, respecti maintain the shank joint angle at 54.6°, and to ensure the

endurance of 2 seconds when the thigh joint angle shifted to
 15° , 35° , 55° , 75° , 85° , and 90° , respectively. Subsequently,

the th Ⅲ.

35.0° 105.5 92.3
45.0° 141.2 139.1
75.0° 170.7 180.3
85.0° 184.5 198.1
90.0° 191.1 205.8
In the kinematic analysis of the integrated leg mechanism,
the gravitational effects of components like servo valves and
hydraulic l 45.0° 141.2 139.1

75.0° 170.7 180.3

85.0° 184.5 198.1

90.0° 191.1 205.8

In the kinematic analysis of the integrated leg mechanism,

the gravitational effects of components like servo valves and

hydraulic lines were o 75.0° 170.7 180.3
 85.0° 184.5 198.1

90.0° 184.5 198.1

In the kinematic analysis of the integrated leg mechanism,

the gravitational effects of components like servo valves and

hydraulic lines were overlooked 75.0° 170.7 180.3

85.0° 184.5 198.1

90.0° 191.1 205.8

In the kinematic analysis of the integrated leg mechanism,

the gravitational effects of components like servo valves and

hydraulic lines were overlooked. This ove 85.0° 184.5 198.1
90.0° 191.1 205.8
191.1 205.8
In the kinematic analysis of the integrated leg mechanism,
the gravitational effects of components like servo valves and
hydraulic lines were overlooked. This oversight led

Upon the completion of the thigh swing condition, the tester readjusted the motion condition of the leg mechanism, as shown in Fig. 12. The thigh joint angle was kept at 75°, and the shank joint angle was stabilized at 41.4°, 66.3°, 91.1°, and 105° for 2 seconds, respectively. Then, the shank joint angle was adjusted back to its initial value, and the next cycle C . of motion began. Three cycles of motion were conducted, and the displacement sensor and force sensor values were collected.

the dynamic model, which then provided the corresponding forces exerted by the shank cylinder. The final comparison between the dynamic model and actual measured data during leg suspension swing is shown in Table Ⅳ.

Fig. 13 Experimental data of shank swing of physical prototype

model modeling, the maximum relative error was found to be 11.8% at a shank joint angle of 105°, while the absolute error was only 6.7 N. Within an acceptable range, it was verified that the dynamic model could effectively solve the shank cylinder force.

C. Strain electrical measurement experiment

Due to the complex force distribution during the operation of the integrated leg mechanism, uniaxial strain gauges and three-axis 45° strain gauges were employed to ensure measurement accuracy. For each uniaxial strain gauge measuring point, the direction of the principal stress σ was known, and the measured strain was the principal strain of the measuring point. When the principal strain ε was measured, Hooke's law could be directly used to calculate the stress value at the measurement point position [18]-[20].

(c)91.1° (d)105° relatively fragile compared to other parts, presenting high stress. More critically, it was also an important part for Fig. 12 The motion conditions of shank suspened swing
transmitting force. Consequently, the measurement points Fig. 13 shows the data on the force sensor of the shank were mainly arranged near the hinge points. As shown in Fig. cylinder within one cycle. Similarly, the average force of the 14 , the numerical numbers $(1-4)$ indicate the location of the shank cylinder was calculated over three cycles, resulting in strain gauges to be pasted, necessitating a total of four strain data for four distinct postures during the suspension swing. gauges. Meanwhile, the letter number (a-g) represents the The cylinder lengths for these postures were then input into
the dynamic model which then provided the corresponding strain rosettes. value at the measurement point position [18]-[20].

TABLE V

PARAMETERS OF STRAIN GAUGE AND STRAIN ROSETTE

Resistance/ Ω Sensitivity

BE-120-3AA-P150 Strain gauge 120.0+0.1 2.17±1%

BE-350-3CA-P100 Strain rosette 350.5+ TABLE V

PARAMETERS OF STRAIN GAUGE AND STRAIN ROSETTE

Resistance/ Ω Sensitivity

BE-120-3AA-P150 Strain gauge

120.0+0.1 2.17±1%

BE-350-3CA-P100 Strain rosette

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The hinge points of the integrated l PARAMETERS OF STRAIN GAUGE AND STRAIN ROSETTE

Resistance/Ω Sensitivity

RE-120-3AA-P150 Strain gauge 120.0+0.1 2.17±1%

BE-350-3CA-P100 Strain rosette 350.5+0.3 2.17±1%

The hinge points of the integrated leg mechanism w **EXECTE ASSOLUTE ASSOCUTE:** Resistance/ Ω
 EXECTED: BE-350-3CA-P100 Strain rosette 350.5±0.3 2.17±1%
 EXECTED: The hinge points of the integrated leg mechanism were relatively fragile compared to other parts, presen RE-120-3AA-P150 Strain gauge

RE-350-3CA-P100 Strain rosette 350.5±0.3 2.17±1%

RE-350-3CA-P100 Strain rosette 350.5±0.3 2.17±1%

The hinge points of the integrated leg mechanism were

relatively fragile compared to other BE-120-3AA-P150 Strain gauge 120.0+0.1 2.17+1%

BE-350-3CA-P100 Strain rosette 350.5+0.3 2.17+1%

The hinge points of the integrated leg mechanism were

relatively fragile compared to other parts, presenting high

stress. BE-350-3CA-P100 Strain rosette 350.5±0.3
The hinge points of the integrated leg r
relatively fragile compared to other parts,
stress. More critically, it was also an im
transmitting force. Consequently, the mea
were mainly

(b)
Fig. 14 Position of test points

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Once it was confirmed that the strain gauges (strain

settes) at each measuring point met the experimental

quirements, the testing system was preheated and cleared

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Once it was confirmed that the strain gauges (strain

rosettes) at each measuring point met the experimental

requirements, the testing system was preheated and cleared

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Once it was confirmed that the strain gauges (strain

rosettes) at each measuring point met the experimental

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Once it was confirmed that the strain gauges (strain

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once it was confirmed that the strain gauges (strain

resettes) at each measuring point met the experimental

requirements, the testing system was preheated and cleared

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Once it was confirmed that the strain gauges (strain

rosettes) at each measuring point met the experimental

requirements, the testing system was preheated and cleared
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26. The shapes of two confirmed that the strain gauges (strain

rosettes) at each measuring point met the experimental

requirements, the testing system was preheated Once it was confirmed that the strain gauges (strain
rosettes) at each measuring point met the experimental
requirements, the testing system was preheated and cleared
to zero in preparation for data collection, while the Once it was confirmed that the strain gauges (strain
rosettes) at each measuring point met the experimental
requirements, the testing system was preheated and cleared
to zero in preparation for data collection, while the Once it was confirmed that the strain gauges (strain
resettes) at each measuring point met the experimental
requirements, the testing system was preheated and cleared and cleared to zero in preparation for data collection rosettes) at each measuring point met the experimental
requirements, the testing system was preheated and cleared
to zero in preparation for data collection, while the leg
of 9.16 kg was supeneed. As shown in Fig. 16 (a), requirements, the testing system was preheated and cleared

to zero in preparation for data collection, while the leg

mechanism was suspended. As shown in Fig. 16 (a), a weight

of 9.16 kg was placed on the sliding suppo to zero in preparation for data collection, while the 1
mechanism was suspended. As shown in Fig. 16 (a), a weig
of 9.16 kg was placed on the sliding support. In the initi
state, the length of the thigh hydraulic cylinder

at the measurement points were recorded, with l1

at the measurement points were conducted, with l1

data for each operating condition of squatting with load

data for each operating condition had stabilized, strain val strain values across different postures with the expected, with $\frac{3}{2}$ and $\frac{1}{2}$ and \frac Fig. 16 Working condition of squating with load

(c)Posture 3

Fig. 16 Working condition of squating with load

A total of 3 cycles of motion were conducted, with 11

measurement points collected from each group. Once the **Example 18**

Fig. 16 Working condition of squatting with load

A total of 3 cycles of motion were conducted, with 11

measurement points collected from each group. Once the

data for each operating condition had stabiliz Example 10.

Fig. 16 Working condition of squatting with load

A total of 3 cycles of motion were conducted, with 11

measurement points collected from each group. Once the

data for each operating condition had stabilized value at the measurement points are presented in Fig. 17 and Table VI.

The measurement points collected from each group. Once the data for each operating condition had stabilized, strain values

at the measurement points (e)Posture 3

Fig. 16 Working condition of squatting with load (e)Test p

A total of 3 cycles of motion were conducted, with 11

measurement points collected from each group. Once the

data for each operating condition ha Fig. 16 Working condition of squatting with load

A total of 3 cycles of motion were conducted, with 11

measurement points collected from each group. Once the

data for each operating condition had stabilized, strain valu

MPa. Following the weighing process, the total weight of the signal maximum of the leg mechanism, peaking at approximately 18

Following the small stress at points and the signal G. Chellapurath M. lacoped and the coording to d 3.86 3.82 3.72 requirements.

f 7.22 5.03 2.38 R

g 1.46 1.33 1.40 II Picardi G, Chellapurah M,

According to Fig. 17, neglecting the small stress at points disturbance," Science Robo

1, 2, 4, b, and e, point 3 had the

For $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ entire machine, the curb weight was 180 kg, and the $\frac{1}{2}$ entire mathine, the curb weight was 180 kg, and the $\frac{1}{2}$ entire mathine, the curb weight of the st EVALUATE THE mathem and the maximum load on a single leg was

the sumall stress for select to the ended disturbance," Science Robotic for sealed

1, 2, 4, b, and e, point 3 had the maximum stress when the

12) Kim TJ, Won **Example 1.46** 1.35 1.40
 Example 1.40 1.35 1.40
 Example 1.40 1.40 legged robot for seabed e

1, 2, 4, b, and e, point 3 had the maximum stress when the

three postures were stable. The stress fluctuated due to the
 According to Fig. 17, neglecting the small stress at points at a considered, boot for seabed explane, and the maximum stress when the

1, 2, 4, b, and e, point 3 had the maximum stress when the

three postters expected, a According to Fig. 17, neglecting the small stress at points

1, 2, 4, b, and e, point 3 had the maximum stress when the

local maximum stress fluctuated due to the

Division Quality of the foot against the ground during t 1, 2, 4, b, and e, point 3 had the maximum stress when the

three postures were stable. The stress fluctuated due to the

three postures were stable. The stress fluctuated due to the

win Quadruped Waking Robot

sidding o three postures were stable. The stress fluctuated due to the

solution of the foot against the ground during the squatting

motion of the leg mechanism, peaking at approximately 18

MPa.

MPa.

Following the weighing proc sliding of the foot against the ground during the squating [3] Mosher R S. "Test am

MDa.

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If wore dings of Off-Roa.

If was approximately 18

If Raibert M. Blankespoor

single leg platform was approximately 36 kg. motion of the leg mechanism, peaking at approximately 18

MPa.

MPa.

Following the weighing process, the total weight of the

ignalized root," *Proceedings of Off-Road Mobilit*

single leg platform was approximately 36 k MPa.

Following the weighing process, the total weight of the Hainbert M, Blankespoor

single leg platform was approximately 36 kg. When installed

on the entire machine, the curb weight was 180 kg, and the

ons the entir Following the weighing process, the total weight of the

single leg platform was approximately 36 kg. When installed

on the entire machine, the curb weight was 180 kg, and the

on the entire machine, the curb weight 70 k single leg platform was approximately 36 kg. When installed

on the entire machine, the curb weight was 180 kg, and the

design maximum load was roughly 70 kg. During the motion

design maximum load was roughly 70 kg. Dur margin. racteristics and impact load of the robot
d the maximum load on a single leg was
aass of the entire machine. By comparing [7]
onship between the load on a single leg
d on a single leg of the complete machine, [8]
t the ma Free considered, and the maximum load on a single leg was

out the full load mass of the entire machine. By comparing and Control Engineering, vol. 225

2011 Control Engineering, vol. 225

2011 Configuration and the load about the full load mass of the entire machine. By comparing [7] Semini C. "HyQ-Design and devel

the numerical relationship between the load on a single leg to the complete machine, [8] LiM, Guo Y, Jiang Z, Ei al. "A sim the numerical relationship between the load on a single leg

platform and the load on a single leg of the complete machine,

it was estimated that the maximum stress on the complete machine,

it was estimated that the max

platform and the load on a single leg of the complete machine,

it was stimated that the maximum stress on the connecting

integation a subsequent boot,

rot gait," In the integrated leg mechanism was approximately 125 [9 It was estimated that the maximum stress on the connecting

13.7, 2012.

It on the integrated leg mechanism was approximately 125 [9] $\frac{1}{2}$ [18] $\frac{1}{2}$ [18] $\frac{1}{2}$ [18] $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\$ rod of the integrated leg mechanism was approximately 125 [9] μ and μ a MPa. The yield strength of the material was compared,

further confirming that the integrated leg mechanism

satisfied the strength requirements and left a certain safety

margin.

Thus Lower Force of $\frac{1}{11}$ Wang L, M the most impurise the more and the integrated leg mechanism and the action and the action of a certain safety

chootic Systems, vol. 14, no. 5, per

Mobiling L, Meng F, Kang R, et in Symmetric Legged Robot of Hill Wang L, satistical the strength requirements and lett a certain satety

margin.

Mobotic Systems, vol. 14, no. 5, pp.

11) Wang L, Meng F, Kang R, et al.

11) Wang L, Meng F, Kang R, et al.

11) Wang L, Meng F, Kang R, et al.

11 margin.

Fig. CoNCLUSION

Herein, the configuration of a innovative integrated leg for

Miga L, Meng F, Kang F, Kang F

legged Robot was investigated and optimized. Initially, an

explicit parameter equation regarding the VIII. CONCLUSION

Merein, the configuration of a innovative integrated leg for

112) Chai H, Meng J, Rong X, et al.

legged robots was investigated and optimized. Initially, an

explicit parameter equation regarding the dy follows: Herein, the configuration of a innovative integrated leg for

gged robots was investigated and optimized. Initially, an

plicit parameter equation regarding the dynamic [13] Jaemin L, Junkyeok

ordinates of the hinge join legged robots was investigated and optimized. Initially, an

explicit parameter equation regarding the dynamic [13] lamin. Junhyeok A Donghynn For

ecoordinates of the hinge joints was established using vector

algebra an explicit parameter equation regarding the dynamic [13] Jamin L, Junkyeok A, Donghyun

coordinates of the hinge joints was established using vector
 $\frac{Fronlies}{Fronlets in Robotics and dM, vol.}$

algebra and linear transformation methods, and th coordinates of the hinge joints was established using vector

algebra and linear transformation methods, and the force of [14] Immanuel P, Jeanette P, C

the hydraulic cylinder was accurately calculated. Segmented Boty Se algebra and linear transformation methods, and the force of [14] Immanuel P, Jeanette P, Cha

the hydraulic cylinder was accurately calculated.

Subsequently, in order to minimize the force of hydraulic $\frac{Engmented Bdds$

Engin

the hydraulic cylinder was accurately calculated. Subsequently cost

Subsequently, in order to minimize the force of hydraulic $\frac{15}{2}$ Zong H, Zhang I, Zha Subsequently, in order to minimize the force of hydraulic

cylinder, the optimization model of the integrated leg

mechanism was established. Ultimately, the effectiveness of *Hydraul*

the mechanism optimization was veri linder, the optimization model of the integrated leg

includ of hydraulic quadrupe

2) the chanism vas setablished. Ultimately, the effectiveness of

2) Interial nonlinearity based

lows:

2) Utilizing the vector algebra mechanism was established. Ultimately, the effectiveness of

the mechanism optimization was verified through

experiments. The research conclusion could be listed as

follows:

follows:

1) Utilizing the vector algebra an the mechanism optimization was verified through $[16]$ supprendict method, the sexerch conclusion could be listed as $\sigma / Advanced Simulation in Sc. 2019$.

1) Utilizing the vector algebra and linear transformation $[17]$ Poningsih, Politak S, experiments. The research conclusion could be listed as

follows:

1) Utilizing the vector algebra and linear transformation

1) Utilizing the vector algebra and linear transformation

1) Poingsin, Poltak S, Muhar

could follows:

1) Utilizing the vector algebra and linear transformation [17] Poinigish, Polaks S, Muhammad Z

methods, the hydraulic cylinder force of the leg mechanism conditions and Diseases," *LAENG*

could be derived by t

improved.

Solution Solution Solution Set the dynamic model and the effect of
3) The effectiveness of the dynamic model and the effect of
2 optimization were both confirmed through suspension
periments. The error of the dynamic mod **al of Applied Mathematics**
3) The effectiveness of the dynamic model and the effect of
the optimization were both confirmed through suspension
experiments. The error of the dynamic model fell within a
reasonable range, an al of Applied Mathematics
3) The effectiveness of the dynamic model and the effect of
the optimization were both confirmed through suspension
experiments. The error of the dynamic model fell within a
reasonable range, and **al of Applied Mathematics**
3) The effectiveness of the dynamic model and the effect of
the optimization were both confirmed through suspension
experiments. The error of the dynamic model fell within a
reasonable range, an **al of Applied Mathematics**
3) The effectiveness of the dynamic model and the ef
the optimization were both confirmed through susp
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reasonable range, and the optimized hydr **of Applied Mathematics**
3) The effectiveness of the dynamic model and the effect of
2 optimization were both confirmed through suspension
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3 asonable range, and the o **al of Applied Mathematics**

3) The effectiveness of the dynamic model and the effect of

the optimization were both confirmed through suspension

experiments. The error of the dynamic model fell within a

reasonable range al of Applied Mathematics

3) The effectiveness of the dynamic model and the effect of

the optimization were both confirmed through suspension

experiments. The error of the dynamic model fell within a

reasonable range,

requirements. Experiments. The error of the dynamic unough suspension
experiments. The error of the dynamic model fell within a
reasonable range, and the optimized hydraulic cylinder force
was reduced by 15%.
4) The actual stress distr Filments. The error of the dynamic model fell within a

ponable range, and the optimized hydraulic cylinder force

reduced by 15%.

The actual stress distribution of the leg mechanism was

ined through strain electrical t onable range, and the optimized hydraulic cylinder force
reduced by 15%.
The actual stress distribution of the leg mechanism was
ined through strain electrical testing experiments, and it
found that the leg mechanism can m was reduced by 15%.

4) The actual stress distribution of the leg mechanism was

obtained through strain electrical testing experiments, and it

was found that the leg mechanism can meet the strength

requirements.

REFER Friend Making Robot, *Property Contention* of the leg mechanism was
ined through strain electrical testing experiments, and it
found that the leg mechanism can meet the strength
irements.
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Picardi G, Chellapura obtained through strain electrical testing experiments, and it

was found that the leg mechanism can meet the strength

requirements.

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