Mechanics of Machines 2nd edition Cleghorn Solutions Manual

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Instructor's Solutions Manual for

MECHANICS OF MACHINES

Second Edition

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William L. Cleghorn
Nikolai Dechev

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P1.1

(a) $r_1 = 2.0 = s$; $r_2 = 6.5 = p$

$r_3 = 3.0 = q$; $r_4 = 7.0 = l$

(i) $l < s + p + q$, ∴ links can form a mechanism

(ii) $s + l = 9.0$, $p + q = 9.5$

$s + l < p + q$, ∴ Class I four-bar kinematic chain

since $r_1 = s$, drag link mechanism

(b) $r_1 = 2.0 = s$; $r_2 = 8.0 = p$

$r_3 = 3.0 = q$; $r_4 = 9.0 = l$

(i) $l < s + p + q$, ∴ links can form a mechanism

(ii) $s + l = 11.0$, $p + q = 11.0$

$s + l = p + q$, ∴ change point mechanism

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P1.1 CONTINUED

(c) $r_1 = 2.5 = l$; $r_2 = 1.0 = s$

$r_3 = 2.5 = p$; $r_4 = 2.0 = q$

(i) $l < s + p + q$, ∴ links can form a mechanism

(ii) $s + l = 3.5$, $p + q = 4.5$

$s + l < p + q$, ∴ Class I four-bar kinematic chain

since $r_2 = s$, crank rocker four-bar mechanism

(d) $r_1 = 2.5 = p$; $r_2 = 3.0 = l$

$r_3 = 1.0 = s$; $r_4 = 2.0 = q$

(i) $l < s + p + q$, ∴ links can form a mechanism

(ii) $s + l = 4.0$, $p + q = 4.5$

$s + l < p + q$, ∴ Class I four-bar kinematic chain

since $r_3 = s$, rocker-rocker four-bar mechanism

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P1.1 CONTINUED

(e) $r_1 = 2.0 = p$; $r_2 = 4.5 = q$

$r_3 = 1.5 = s$; $r_4 = 9.0 = l$

(i) $l > s + p + q$, ∴ links cannot form a mechanism

(f) $r_1 = 1.5 = s$; $r_2 = 3.0 = p$

$r_3 = 2.5 = q$; $r_4 = 6.0 = l$

(i) $l < s + p + q$, ∴ links can form a mechanism

(ii) $s + l = 7.5$, $p + q = 5.5$

$s + l > p + q$, rocker - rocker four-bar mechanism

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P1.2

$r_1 = 1.0$; $r_3 = 2.5$; $r_4 = 2.0$

(a) to be a crank rocker mechanism, r_2 must be the shortest link (i.e., $r_2 < 1.0$)
also, we require $s + l < p + q$ ($s = r_2$; $l = r_3 = 2.5$; $p = r_1 = 1.0$; $q = r_4 = 2.0$)

$$r_2 + 2.5 < 1.0 + 2.0$$

$$r_2 < 0.5$$

(b) to be a drag link mechanism, r_1 must be the shortest link (i.e., $r_2 > 1.0$)
r_2 may be p, q or l.

Case 1 : if r_2 is l ($r_1 = s$, $r_3 = p$, $r_4 = q$)

$$s + l < p + q$$

$$1.0 + r_2 < 2.5 + 2.0 \quad , \quad r_2 < 3.5$$

Case 2 : if $r_2 = p$ or q ($r_1 = s$, $r_3 = l$, $r_4 = q$ or p)

$$s + l < p + q$$

$$1.0 + 2.5 < r_2 + 2.0 \quad , \quad r_2 > 1.5$$

combining Cases 1 and 2: $1.5 < r_2 < 3.5$

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P1.2 CONTINUED

(c) to be a change point mechanism, $s+l = p+q$

Case 1 : if $r_2 = s$ ($r_1 = p$, $r_3 = l$, $r_4 = q$)

$s + l = p + q$

$r_2 + 2.5 = 1.0 + 2.0$, $r_2 = 0.5$

Case 2 : if $r_2 = l$ ($r_1 = s$, $r_3 = p$, $r_4 = q$)

$s + l = p + q$

$1.0 + r_2 = 2.5 + 2.0$, $r_2 = 3.5$

Case 3 : if $r_2 = p$ ($r_1 = s$, $r_3 = l$, $r_4 = q$)

$s + l = p + q$

$1.0 + 2.5 = r_2 + 2.0$, $r_2 = 1.5$

combining Cases 1, 2 and 3: $r_2 = 0.5$ OR
$r_2 = 1.5$ OR
$r_2 = 3.5$

(d) to be a rocker-rocker mechanism, $s+l > p+q$

Case 1 : if $r_2 = s$

$s + l > p + q$

$r_2 + 2.5 > 1.0 + 2.0$, $r_2 > 0.5$ (i)

also, because r_2 is the shortest link, $r_2 < 1.0$ (ii)

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P1.2 CONTINUED

combining (i) and (ii) : $0.5 < r_2 < 1.0$ (I)

Case 2 : if $r_2 = l$

$s + l > p + q$

$1.0 + r_2 > 2.0 + 2.5$, $r_2 > 3.5$ (iii)

also, for assembly of the kinematic chain,

$s + p + q > l$

$1.0 + 2.0 + 2.5 > r_2$, $r_2 < 5.5$ (iv)

combining (iii) and (iv) : $3.5 < r_2 < 5.5$ (II)

Case 3 : if $r_2 = p$

$s + l > p + q$

$1.0 + 2.5 > r_2 + 2.0$, $r_2 < 1.5$ (v)

but for this case, r_2 cannot be the shortest link, and therefore $r_2 \geq 1.0$ (vi)

combining (v) and (vi) : $1.0 \leq r_2 < 1.5$ (III)

combining (I), (II) and (III)

$0.5 < r_2 < 1.5$ OR $3.5 < r_2 < 5.5$

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P1.3

$r_1 = 1.0$; $r_2 = 3.0$; $r_3 = 2.5$

(a) to be a crank rocker mechanism, the input link must be the shortest link
considering r_4 as the input link

$s + l < p + q$

$r_4 + 3.0 < 1.0 + 2.5, \quad r_4 < 0.5$

(b) to be a drag link mechanism, the base link length, r_1, must be the shortest link
thus, r_4 may be p, q or l

Case 1: if $r_4 = l$

$s + l < p + q$

$1.0 + r_4 < 3.0 + 2.5, \quad r_4 < 4.5$

also, for r_4 to be the longest link, $r_4 > 3.0$

$\therefore 3.0 < r_4 < 4.5$

Cas 2: if $r_4 = p$ or q

$s + l < p + q$

$1.0 + 3.0 < 2.5 + r_4, \quad r_4 > 1.5$

also, for r_4 to be p or q, $r_4 \leq 3.0$

$\therefore 1.5 < r_4 \leq 3.0$

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P1.3 CONTINUED

(c) to be a change point mechanism: $s+l = p+q$

Case 1: $r_4 = s$

$s + l = p + q$

$r_4 + 3.0 = 1.0 + 2.5, \quad r_4 = 0.5$

Case 2: $r_4 = l$

$s + l = p + q$

$1.0 + r_4 = 2.5 + 3.0, \quad r_4 = 4.5$

Case 3: $r_4 = p$ or q

$1.0 + 3.0 = r_4 + 2.5, \quad r_4 = 1.5$

combining Cases 1, 2 and 3: $r_4 = 0.5$ OR
$r_4 = 1.5$ OR
$r_4 = 4.5$

(d) to be a rocker-rocker mechanism, $s + l > p + q$

Case 1: $r_4 = s$

$r_4 + 3.0 > 1.0 + 2.5, \quad r_4 > 0.5$

also, for r_4 to be the shortest link, $r_4 \leq 1.0$

$\therefore \; 0.5 < r_4 \leq 1.0 \quad (I)$

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P1.3 CONTINUED

Case 2: $r_4 = p$ or q

$s + l > p + q$

$1.0 + 3.0 > r_4 + 2.5, \quad r_4 < 1.5 \quad (i)$

also, because r_4 cannot be the shortest link,
$r_4 \geq 1.0 \quad (ii)$

combining (i) and (ii): $1.0 \leq r_4 < 1.5 \quad (II)$

Case 3: $r_4 = l$

$s + l > p + q$

$1.0 + r_4 > 2.5 + 3.0, \quad r_4 > 4.5 \quad (iii)$

also, for assembly of the kinematic chain,

$s + p + q > l$

$1.0 + 2.5 + 3.0 > r_4, \quad r_4 < 6.5 \quad (iv)$

combining (iii) and (iv): $4.5 < r_4 < 6.5 \quad (III)$

combining (I), (II) and (III): $0.5 < r_4 < 1.5$ OR
$4.5 < r_4 < 6.5$

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P1.4

$r_1 = 1.0\,cm$; $r_3 = 2.5\,cm$

(a) for full rotation of link 2:

(i) $r_2 < r_3$ and (ii) $|r_1| \leq r_3 - r_2$

$\therefore$ (i) $r_2 < 2.5\,cm$

(ii) $|r_1| \leq r_3 - r_2$

$1.0 \leq 2.5 - r_2$, $r_2 \leq 1.5\,cm$

combining (i) & (ii), conclude $\underline{r_2 \leq 1.5\,cm}$

(b) possible to assemble mechanism:

$|r_1| \leq r_2 + r_3$

$1.0 \leq r_2 + 2.5$, $r_2 \geq -1.5\,cm$

from which we conclude $\underline{r_2 \geq 0}$

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P1.5

$r_1 = 1.0\text{cm}$; $r_2 = 2.5\text{cm}$

(a) for full rotation of link 2:

(i) $r_2 < r_3$ and (ii) $|r_1| \leq r_3 - r_2$

$\therefore$ (i) $2.5 < r_3$, $r_3 > 2.5\text{cm}$

(ii) $|r_1| \leq r_3 - r_2$

$1.0 \leq r_3 - 2.5$, $r_3 \geq 3.5\text{cm}$

combining (i) & (ii), conclude $\underline{r_3 \geq 3.5\text{cm}}$

(b) possible to assemble mechanism:

$|r_1| \leq r_2 + r_3$

$1.0 \leq 2.5 + r_3$, $r_3 \geq -1.5\text{cm}$

from which we conclude $\underline{r_3 \geq 0}$

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P1.6

(a) $r_3 = 3.5\,cm$

$s = r_2 = 2.0cm$; $p = r_3 = 3.5cm$

$l = r_1 = 7.0cm$; $q = r_4 = 6.0cm$

$(s + l = 9.0cm) < (p + q = 9.5cm)$

∴ class I four-bar mechanism
since s is the input link, crank rocker

(b) $r_3 = 11.0cm$

$s = r_2 = 2.0cm$; $p = r_4 = 6.0cm$

$l = r_3 = 11.0cm$; $q = r_1 = 7.0cm$

$(s + l = 13.0cm) = (p + q = 13.0cm)$

∴ change point

(c) $r_3 = 11.5\,cm$

$s = r_2 = 2.0cm$; $p = r_4 = 6.0cm$

$l = r_3 = 11.5cm$; $q = r_1 = 7.0cm$

$(s + l = 13.5cm) > (p + q = 13.0cm)$

∴ class II four-bar mechanism
rocker-rocker

P1.7

crank rocker (a)

the input motion to the four-bar mechanism is the gear (i.e., crank) that executes full rotations

the output motion of the four-bar mechanism is the gear sector (i.e., rocker) that oscillates between two limit positions

the gear sector drives a smaller gear that is rigidly connected to the agitator that undergoes oscillatory motion and provides the washing action

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P1.8

crank rocker (a)

the input motion to the four-bar mechanism executes full rotations

the output motion of the four-bar mechanism is the coupler point on the coupler that enters a perforation in the film. The coupler point then advances the film by one frame

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P1.9

(a) $n = 6$

- turning pairs, 5 ;
- sliding pair, 1 ;
- rolling pair, 1 $(j_1 = 5 + 1 + 1 = 7)$
- 2 dof pairs, $(j_2 = 0)$

$$m = 3(n-1) - 2j_1 - j_2$$
$$= 3(6-1) - 2 \times 7 = 1$$

(b) $n = 6$

- turning pairs, 5;
- sliding pairs, 2 ;
- rolling pairs, 0 $(j_1 = 5 + 2 + 0 = 7)$
- 2 dof pairs, 0 $(j_2 = 0)$

$$m = 3(n-1) - 2j_1 - j_2$$
$$= 3(6-1) - 2 \times 7 = 1$$

P1.10

(a) $n = 4, \quad j_1 = 4, \quad j_2 = 0$

$$m = 3(n-1) - 2j_1 - j_2$$
$$= 3(4-1) - 2 \times 4 = 1$$

(b) $n = 6, \quad j_1 = 7, \quad j_2 = 0$

$$m = 3(6-1) - 2 \times 7 = 1$$

P1.11

(a) $n = 6$

- turning pairs, 7 ;
- sliding pairs, 0 ;
- rolling pairs, 0 $(j_1 = 7+0+0 = 7)$
- 2 dof pairs, 0 $(j_2 = 0)$

$$m = 3(n-1) - 2j_1 - j_2$$
$$= 3(6-1) - 2\times 7 = 1$$

(b) $n = 8$

- turning pairs, 10;
- sliding pairs, 0 ;
- rolling pairs, 0 $(j_1 = 10+0+0 = 10)$
- 2 dof pairs, 0 $(j_2 = 0)$

$$m = 3(n-1) - 2j_1 - j_2$$
$$= 3(8-1) - 2\times 10 = 1$$

P1.12

(a) $n = 4$

- turning pairs, 0 ;
- sliding pairs, 5 ;
- rolling pairs, 0 $\quad (j_1 = 0 + 5 + 0 = 5)$
- 2 dof pairs, 0 $\quad (j_2 = 0)$

$$m = 3(n-1) - 2j_1 - j_2$$
$$= 3(4-1) - 2 \times 5 = -1$$

- however, there are two redundant constraints (i.e., $N_R = 2$)

- relative rotations between links 2 and 3, and between links 3 and 4 are accounted for twice (once by sliding pairs between links 2 and 3, and between links 3 and 4; and then again by sliding pairs between links 1 and 2, 1 and 3, and 1 and 4)

$\therefore \quad m = 3(n-1) - 2j_1 - j_2 + N_R = 1$

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P1.12 CONTINUED

(b) $n = 4$

- turning pairs, 0;
- sliding pairs, 3;
- rolling pairs, 0 $(j_1 = 0+3+0 = 3)$
- 2 dof pairs, 2 $(j_2 = 2)$

$$m = 3(n-1) - 2j_1 - j_2$$
$$= 3(4-1) - 2\times 3 - 2 = 1$$

P1.13

(a) $n = 4$

- turning pairs, 3;
- sliding pairs, 0;
- rolling pairs, 2 $(j_1 = 3 + 0 + 2 = 5)$
- 2 dof pairs, 0 $(j_2 = 0)$

$$m = 3(n-1) - 2j_1 - j_2$$
$$= 3(4-1) - 2\times 5 - 0 = -1$$

- however, there are two redundant constraints (i.e., $N_R = 2$)

- distances between base pivots of links 2 and 3, and between base pivots of links 3 and 4 are accounted for twice (once by rolling pairs between links 2 and 3, and between links 3 and 4; and then again by base pivots of link 2 and 3, and base pivots of links 3 and 4)

$$\therefore m = 3(n-1) - 2j_1 - j_2 + N_R = 1$$

P1.13 CONTINUED

(b) $n = 8$

- turning pairs, 9;
- sliding pairs, 0;
- rolling pairs, 2 $(j_1 = 9 + 0 + 2 = 11)$
- 2 dof pairs, 0 $(j_2 = 0)$

$$m = 3(n-1) - 2j_1 - j_2$$
$$= 3(8-1) - 2 \times 11 = -1$$

- however, the above calculation incorporates two redundant constraints (same as for P1.5(a))

$$N_R = 2$$

$$\therefore \; m = 3(n-1) - 2j_1 - j_2 + N_R = 1$$

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P1.14

4 links, $n = 4$

4 turning pairs,

0 rolling pairs,

0 sliding pairs, $j_1 = 0 + 4 + 0 = 4$

0 DOF pairs, $j_2 = 0$

no redundant constraints, $N_R = 0$

$m = 3\ (n - 1) - 2\ j_1 - j_2 + N_R = 1$

P1.15

4 links, $n = 4$

4 turning pairs,

0 rolling pairs,

0 sliding pairs, $j_1 = 0 + 4 + 0 = 4$

0 DOF pairs, $j_2 = 0$

no redundant constraints, $N_R = 0$

$m = 3\,(n - 1) - 2\,j_1 - j_2 + N_R = 1$

P1.16

3 links, $n = 3$

1 turning pair,

1 rolling pair,

1 sliding pair, $j_1 = 1 + 1 + 1 = 3$

0 DOF pairs, $j_2 = 0$

one redundant constraints, $N_R = 1$

$m = 3\,(n - 1) - 2\,j_1 - j_2 + N_R = 1$

P1.17

4 links, $n = 4$

2 turning pairs,

1 rolling pairs,

1 sliding pairs, $j_1 = 2 + 1 + 1 = 4$

0 DOF pairs, $j_2 = 0$

no redundant constraints, $N_R = 0$

$m = 3\,(n - 1) - 2\,j_1 - j_2 + N_R = 1$

P1.18

(a) $n = 5$; $j_1 = 6$; $j_2 = 0$

$N_R = 1$ (center-to-center distance between O_5 & E accounted for length of link 5 AND lengths of $r_{O_4O_5}$, r_{O_4D} & r_{DE}

$$m = 3(n-1) - 2j_1 - j_2 + N_R$$
$$= 3(5-1) - 2\times 6 - 0 + 1 = 1$$

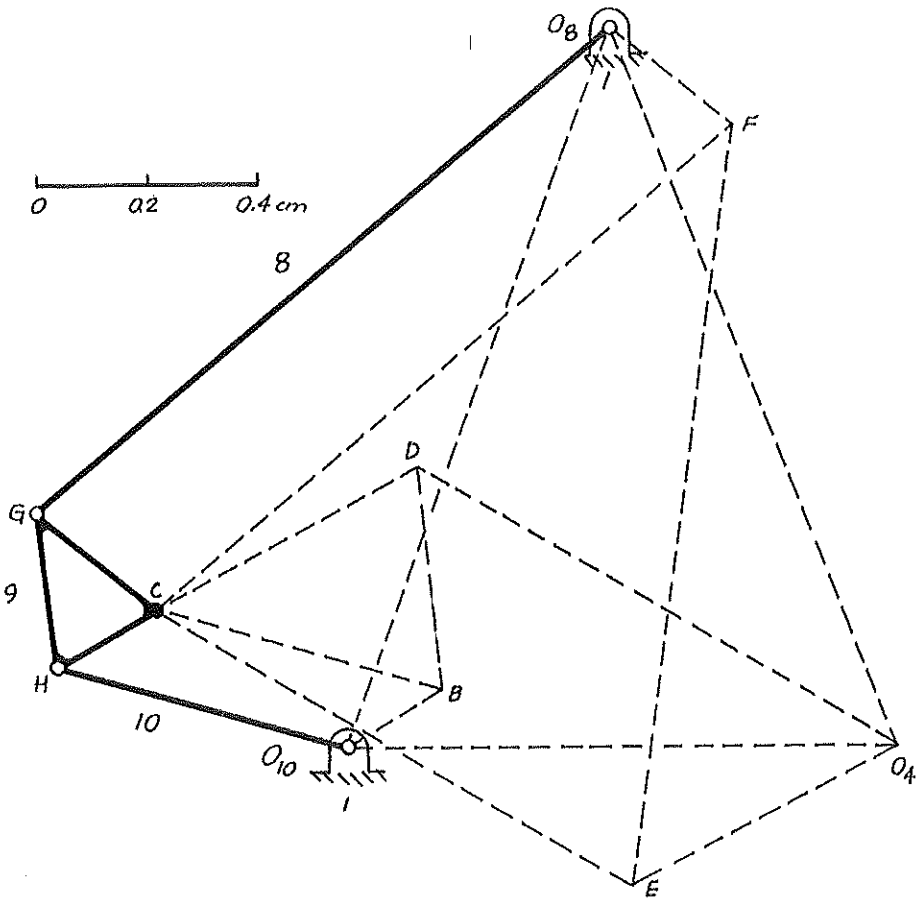
(b) $n = 6$; $j_1 = 8$; $j_2 = 0$

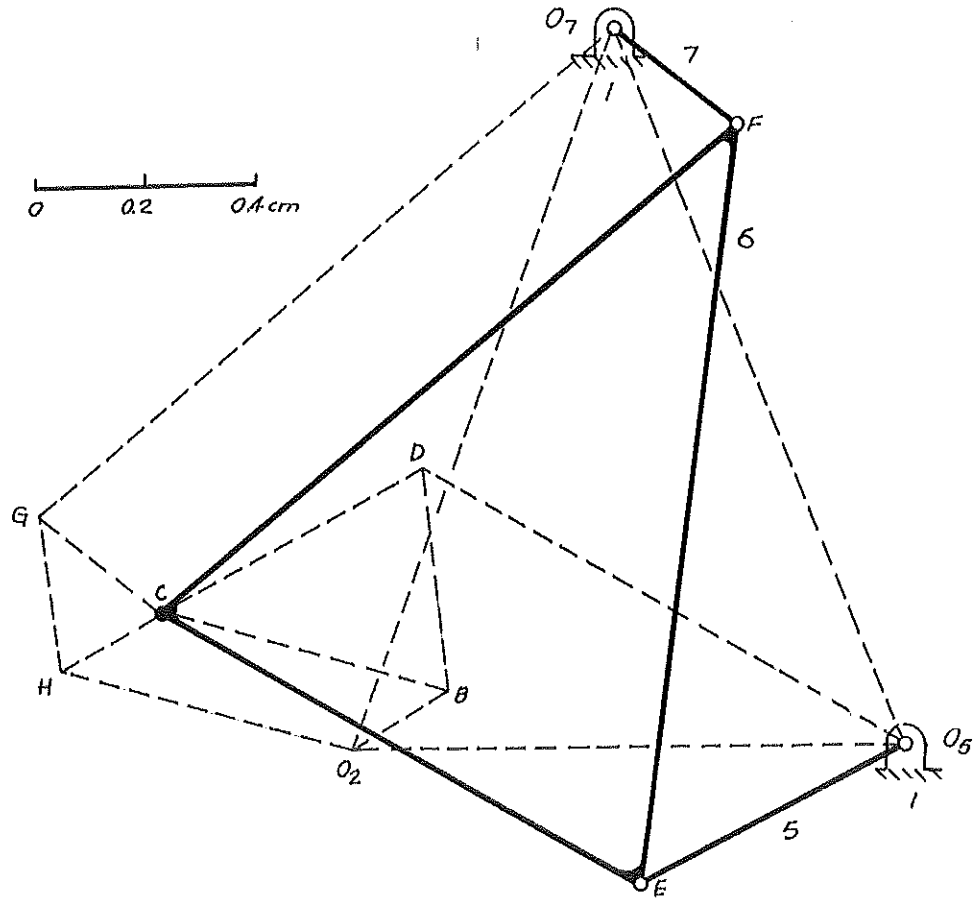
$N_R = 2$ (center-to-center distance between O_5 & E accounted for length of link 5 AND lengths of $r_{O_4O_5}$, r_{O_4D} & r_{DE}; similar reasoning for length r_{O_6F})

$$m = 3(n-1) - 2j_1 - j_2 + N_R = 1$$

P1.19

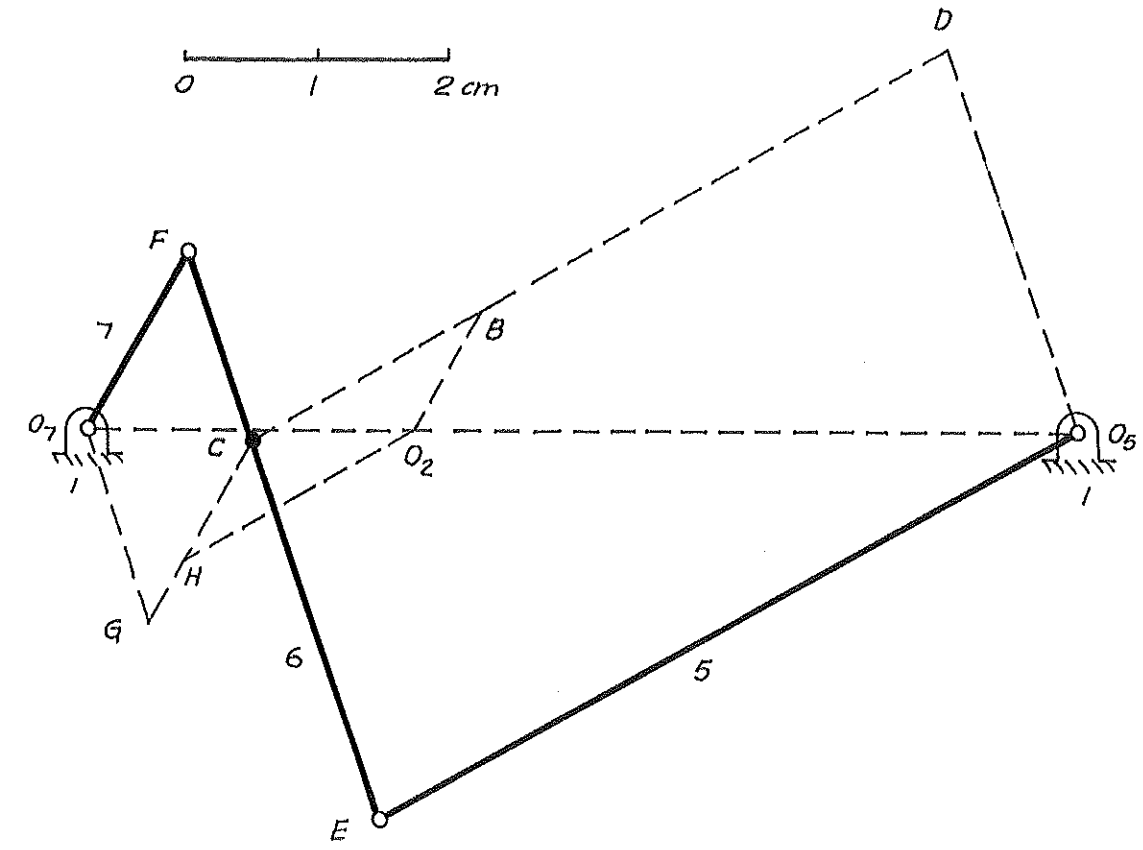
(a)

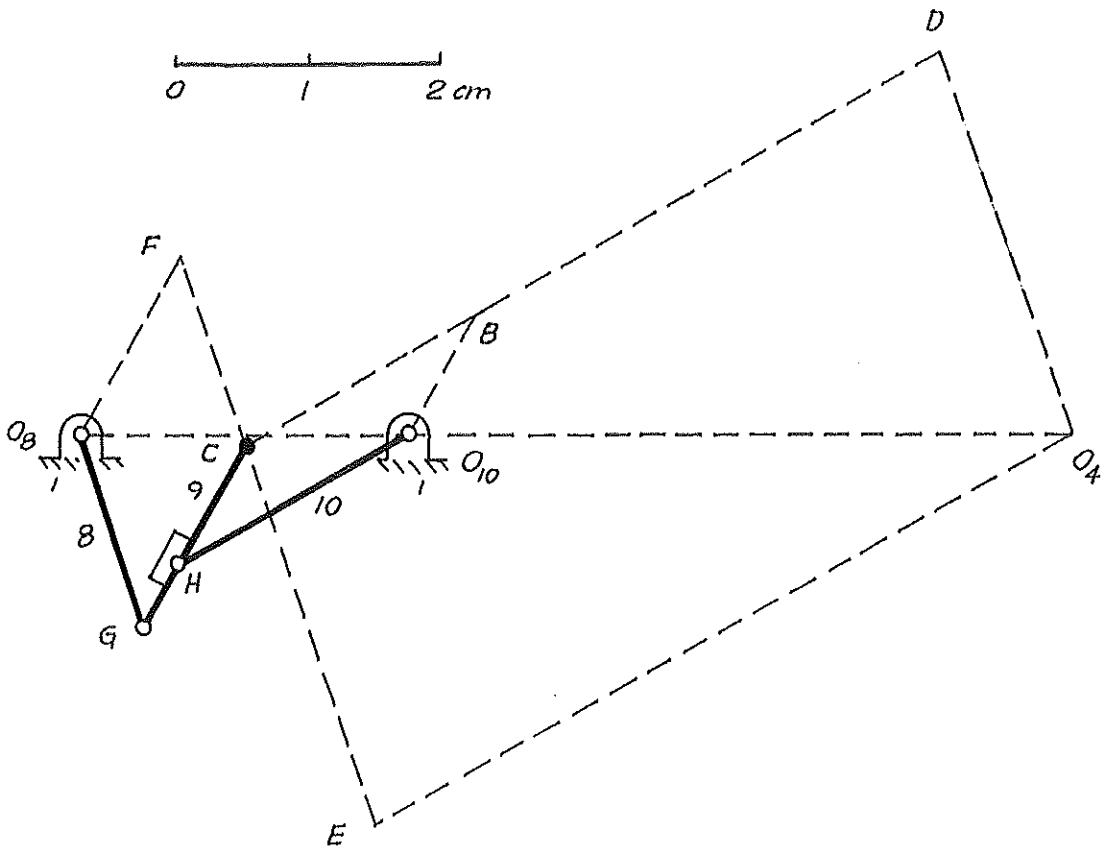

O_8
F
0
0.2
0.4 cm
8
D
G
9
C
H
B
10
O_{10}
1
O_4
E


O_7
7
1
F
0
0.2
0.4 cm
6
D
G
C
H
B
O_2
O_6
1
5
E

P1.19 CONTINUED

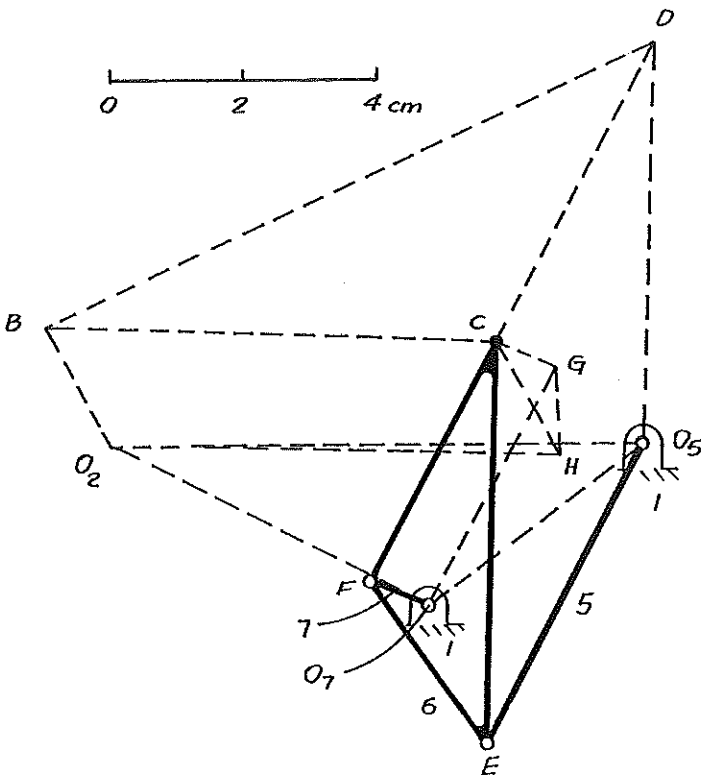
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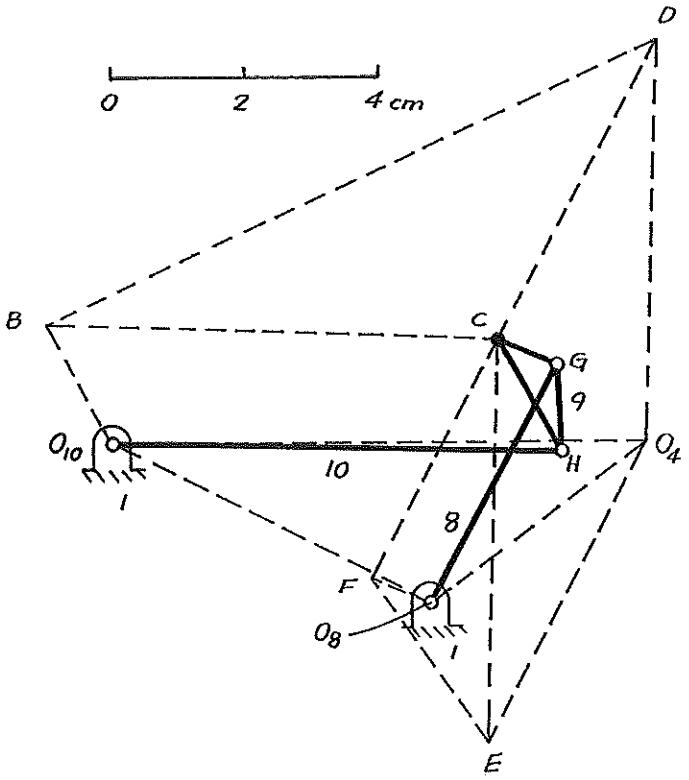




P1.19 CONTINUED

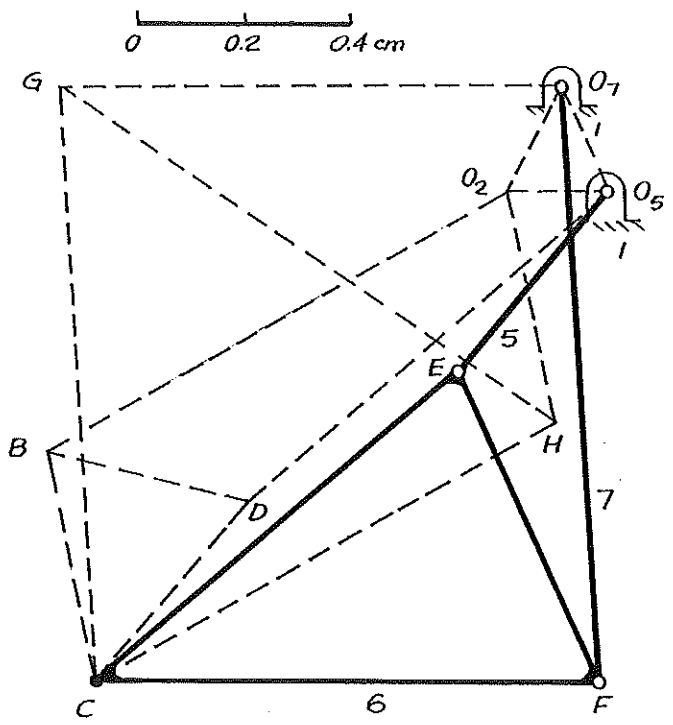
(c)

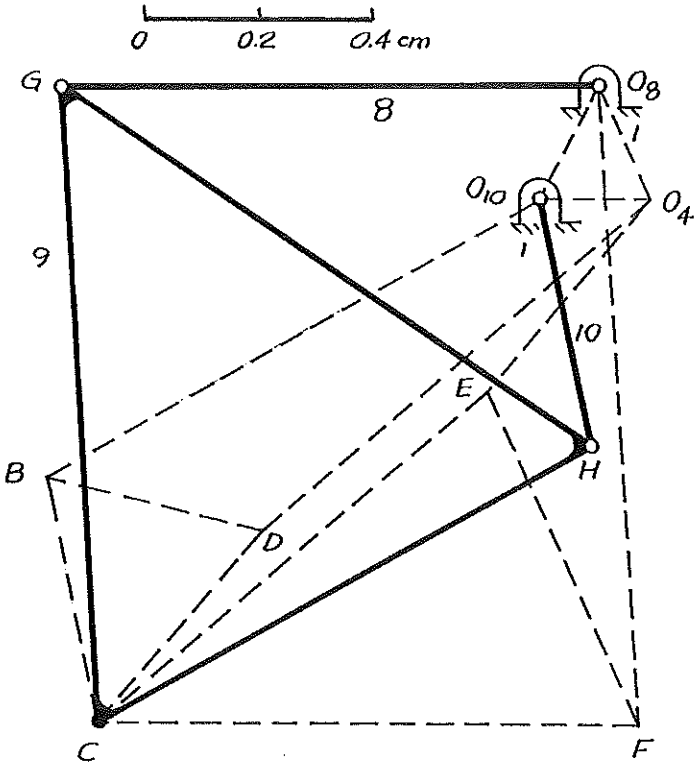




P1.19 CONTINUED

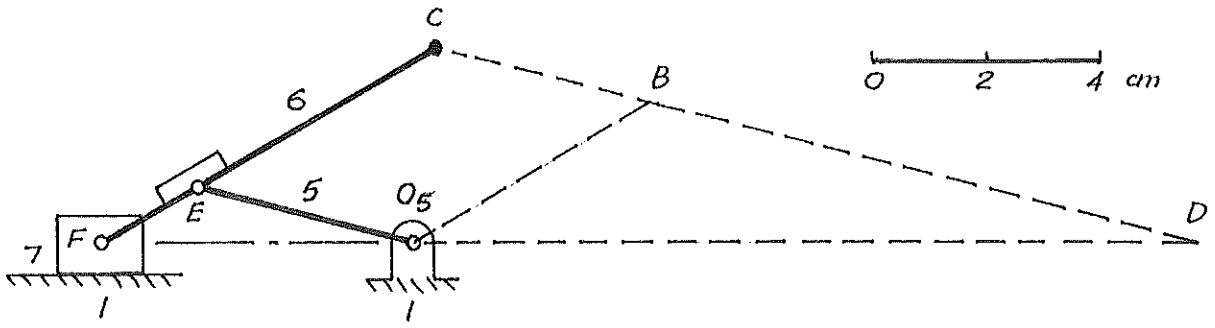
(d)



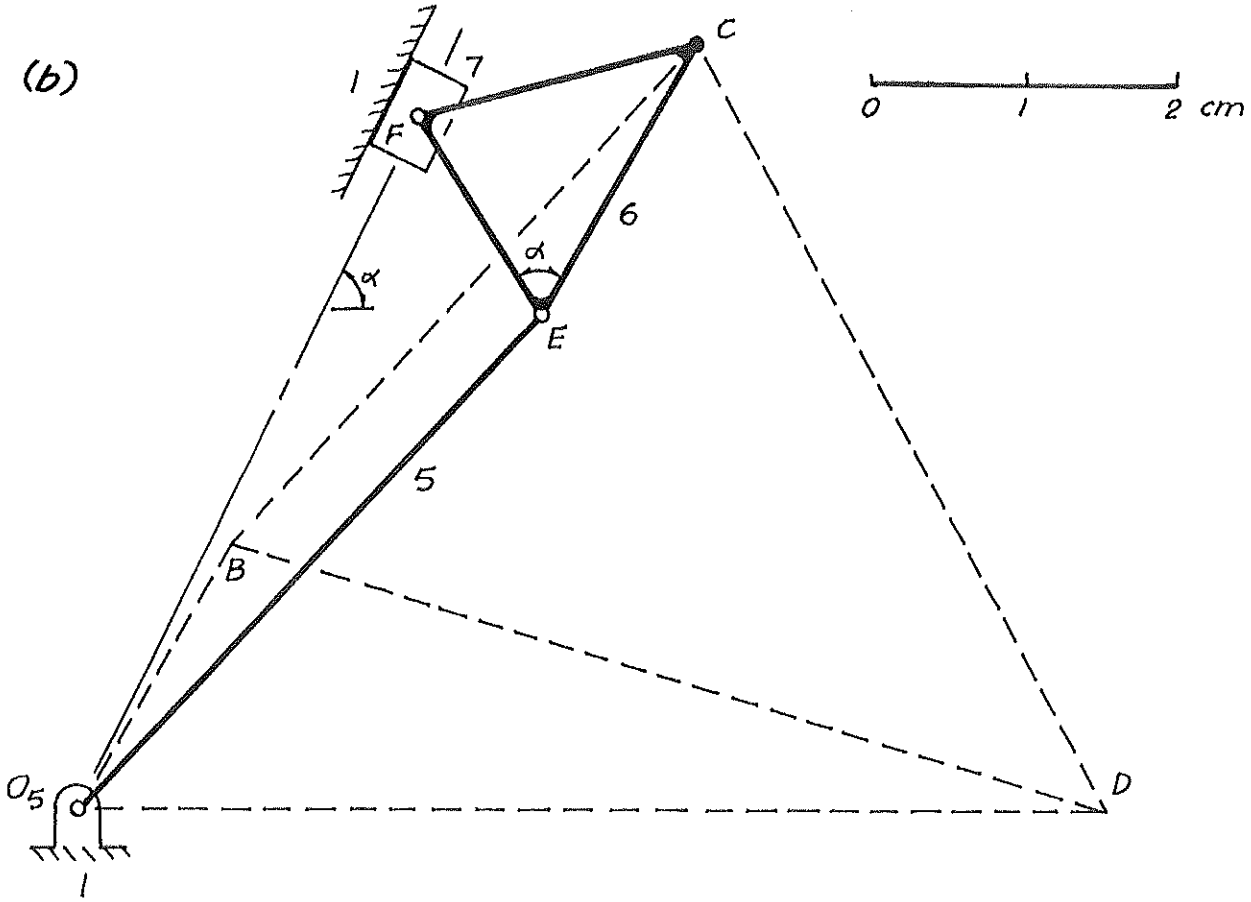


P1.20

(a)

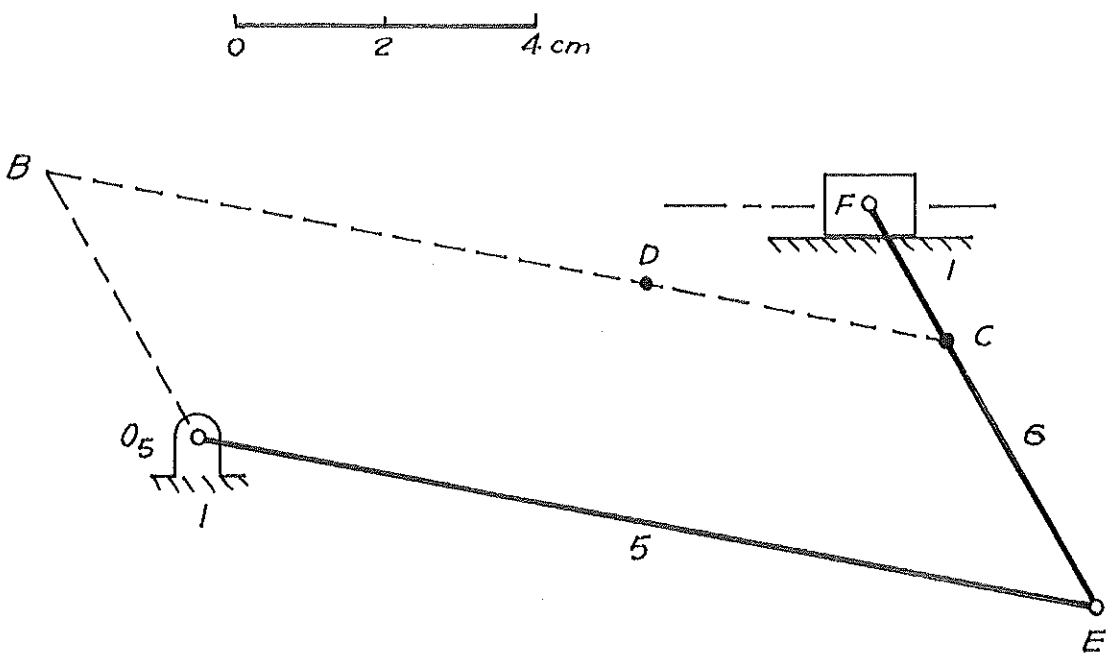


(b)

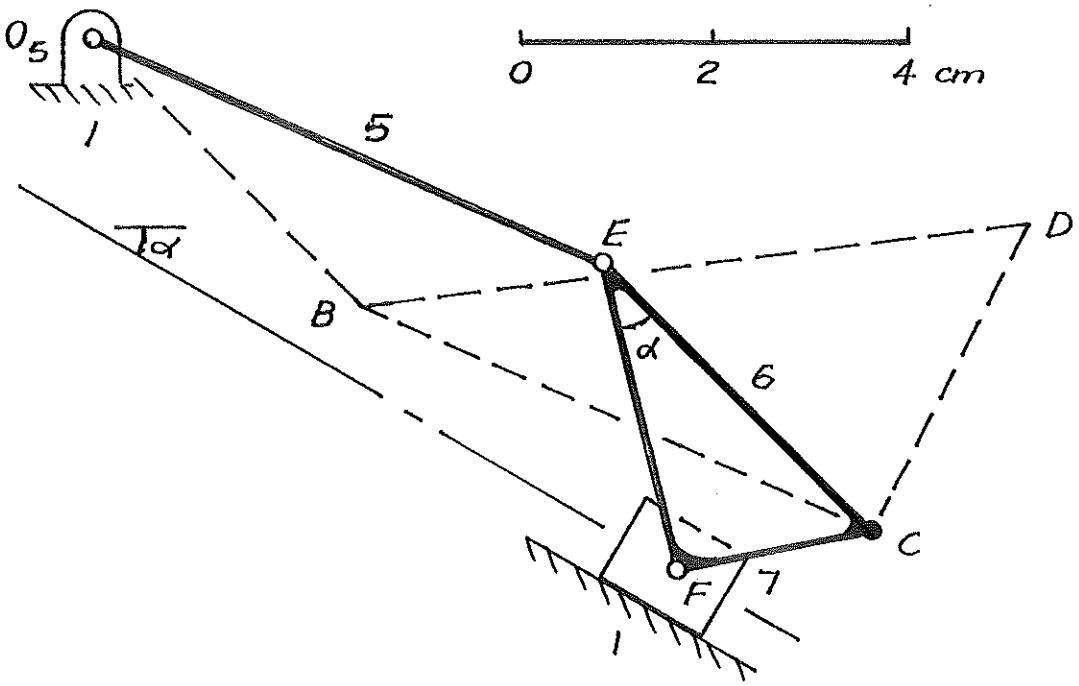


P1.20 CONTINUED

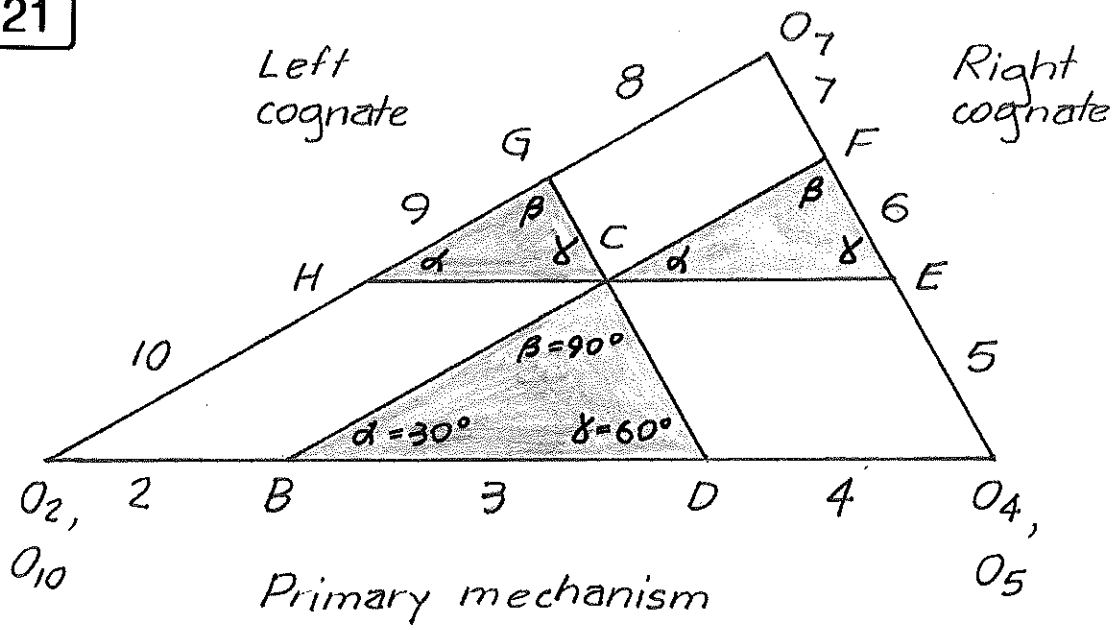
(c)



(d)



P1.21



Left cognate:

base link: $r_{O_8 O_{10}} = 11.8$ cm;

link 8: $r_{O_8 G} = 6.00$ cm; link 9: $r_{GH} = 4.33$ cm;

link 10: $r_{O_{10} H} = 7.79$ cm

Right cognate:

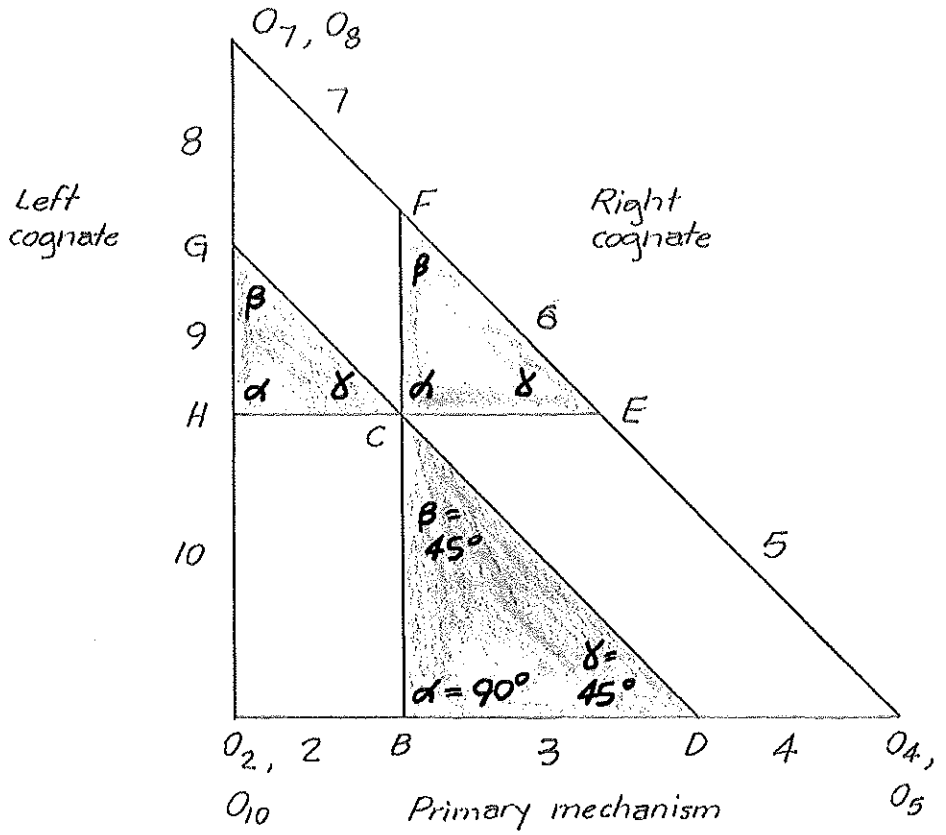
base link: $r_{O_5 O_7} = 6.50$ cm;

link 5: $r_{O_5 E} = 4.50$ cm; link 6: $r_{EF} = 3.00$ cm;

link 7: $r_{O_7 F} = 2.50$ cm

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P1.22



Left cognate:

base link: $r_{O_8O_{10}} = 12.0\,cm$;

link 8: $r_{O_8G} = 6.00\,cm$; link 9: $r_{GH} = 5.00\,cm$;

link 10: $r_{O_{10}H} = 9.00\,cm$

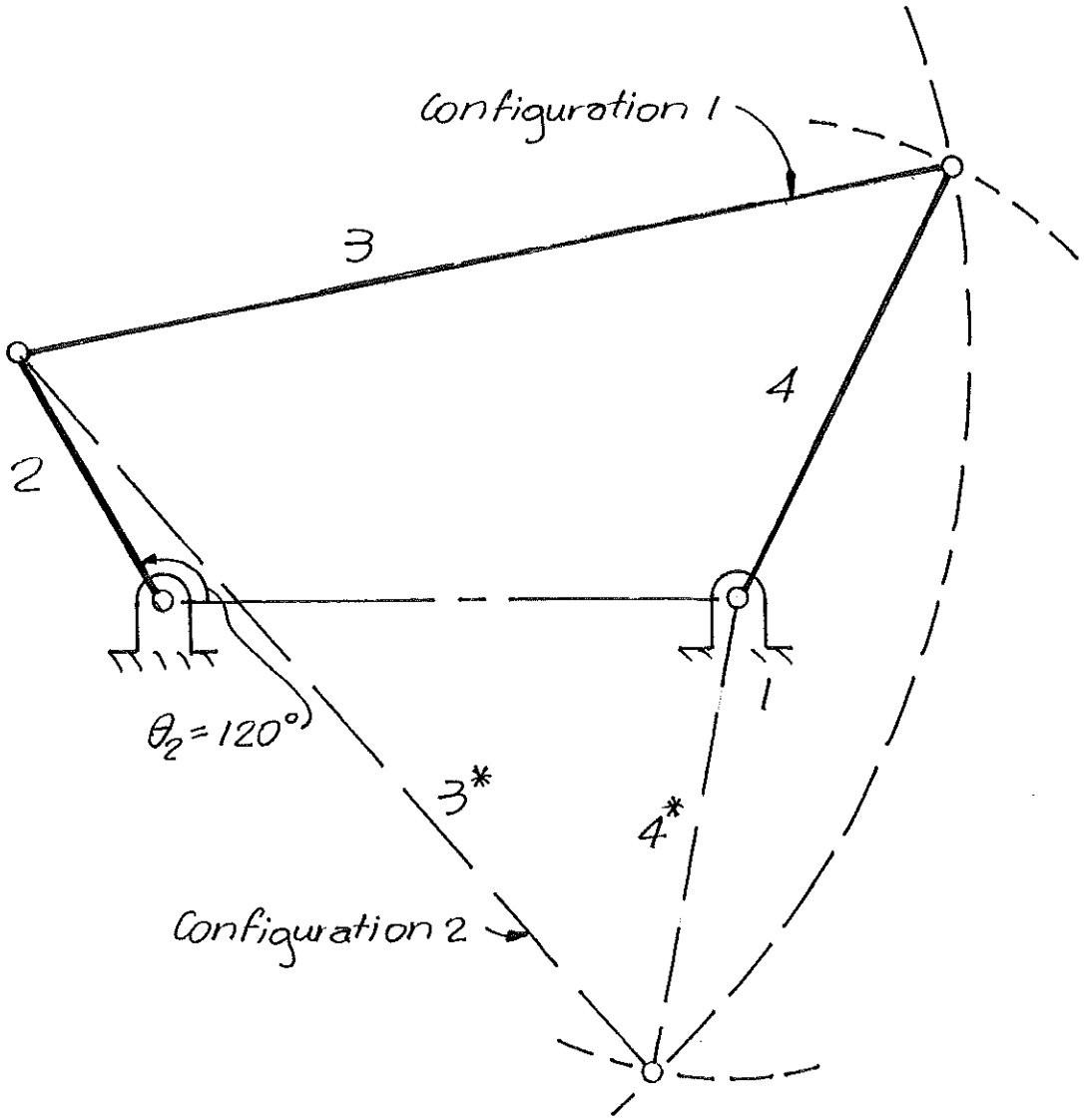
Right cognate:

base link: $r_{O_5O_7} = 17.0\,cm$;

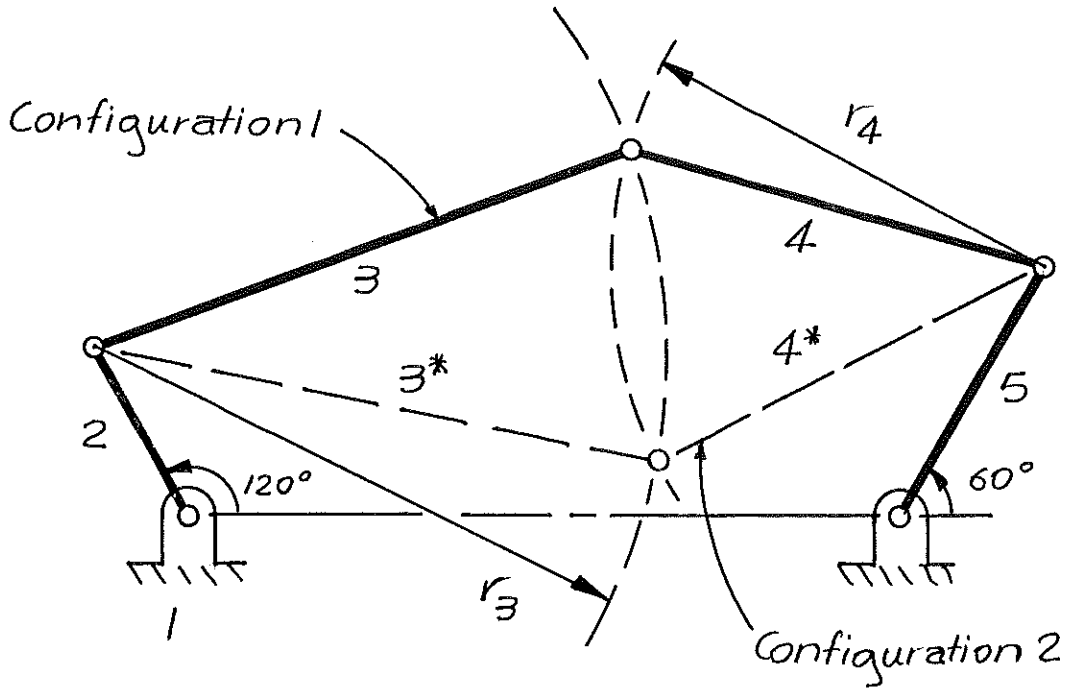
link 5: $r_{O_5E} = 12.7\,cm$; link 6: $r_{EF} = 8.49\,cm$;

link 7: $r_{O_7F} = 7.07\,cm$

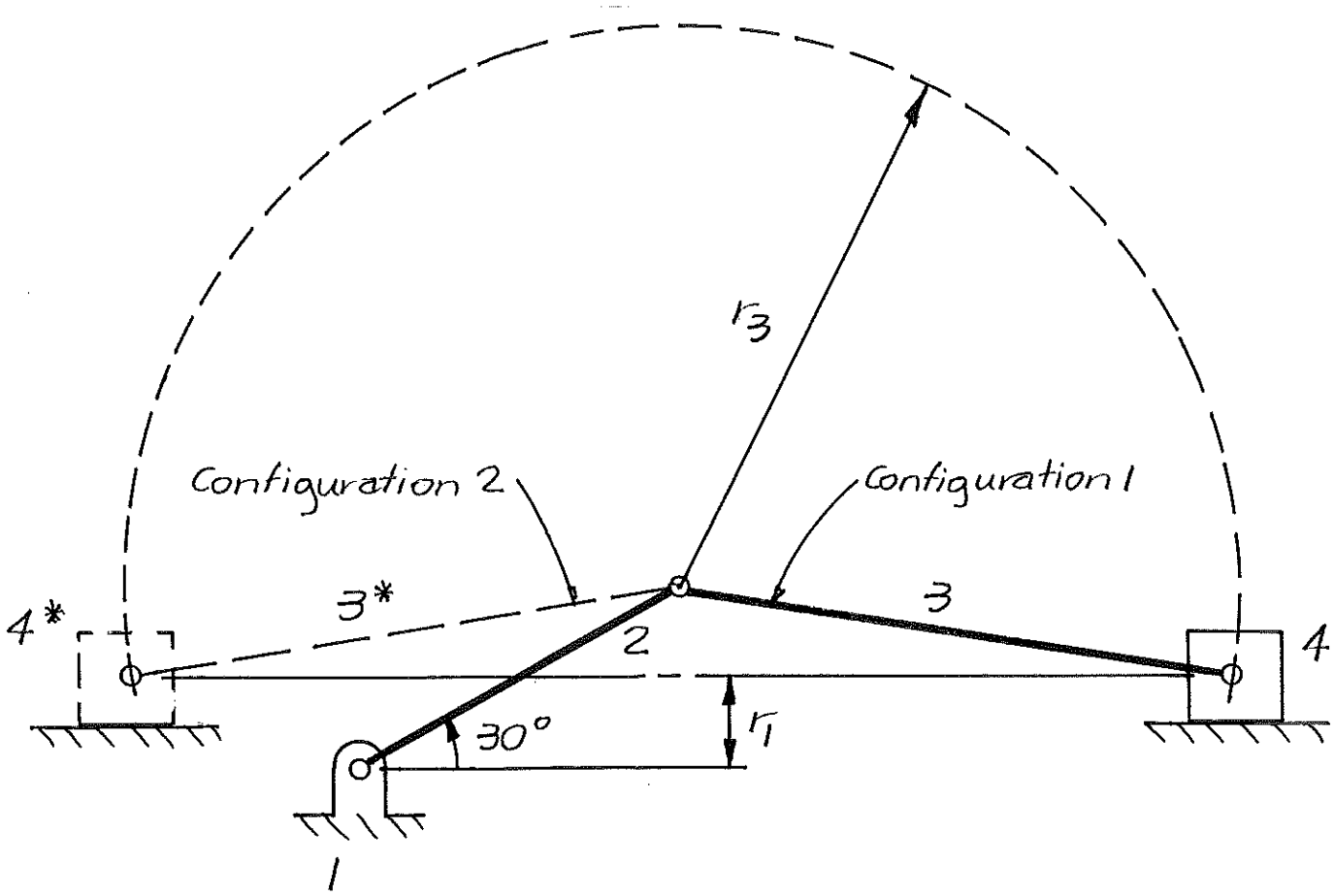
P2.1



P2.2

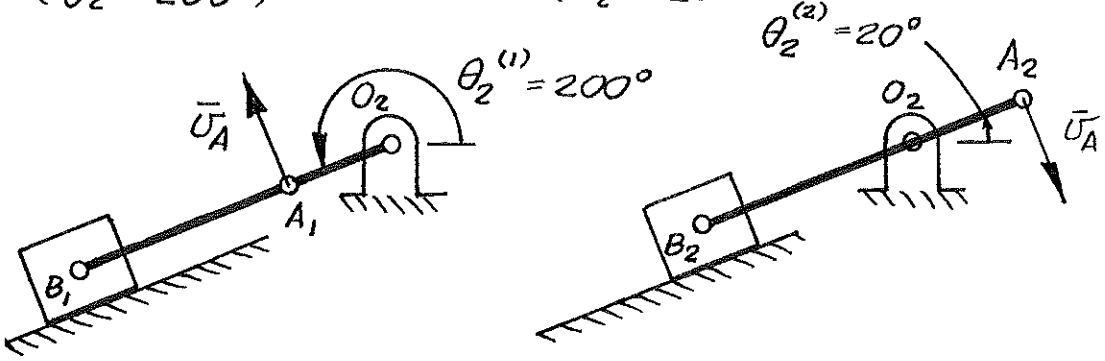


P2.3



P2.4

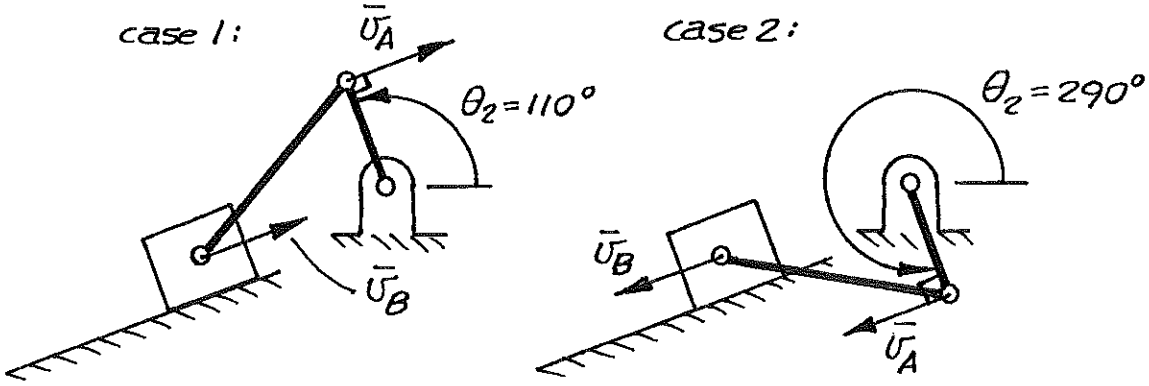
(a) limit position 1: ($\theta_2^{(1)} = 200°$) limit position 2: ($\theta_2^{(2)} = 20°$)



for both limit geometries

$$|\dot{\theta}_3| = \frac{v_A}{r_{AB}} = \frac{r_{AO_2}|\dot{\theta}_2|}{r_{AB}} = \frac{3.0 \times 100}{6.0} = 50 \text{ rpm}$$

(b) rotational speed of link 3 is zero when $\bar{v}_A$ and $\bar{v}_B$ have the same direction



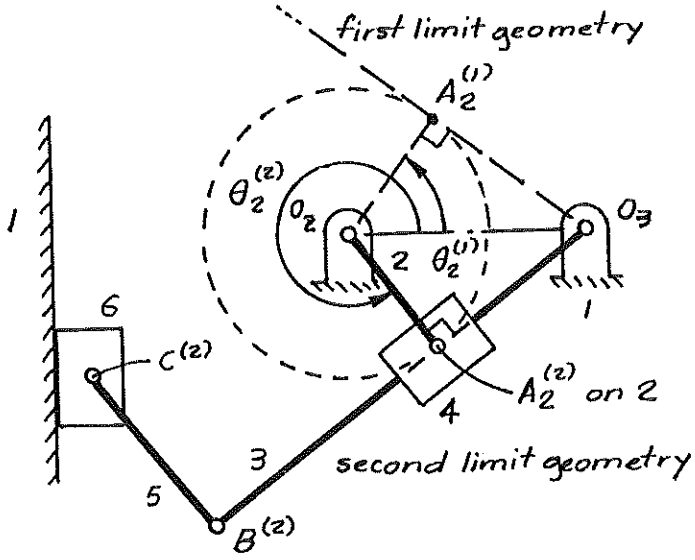
for both cases $\underline{v_B = r_{AO_2}|\dot{\theta}_2| = 3.0 \times 100 \times \frac{2\pi}{60}}$

$$\underline{= 31.4 \frac{\text{cm}}{\text{sec}}}$$

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P2.5

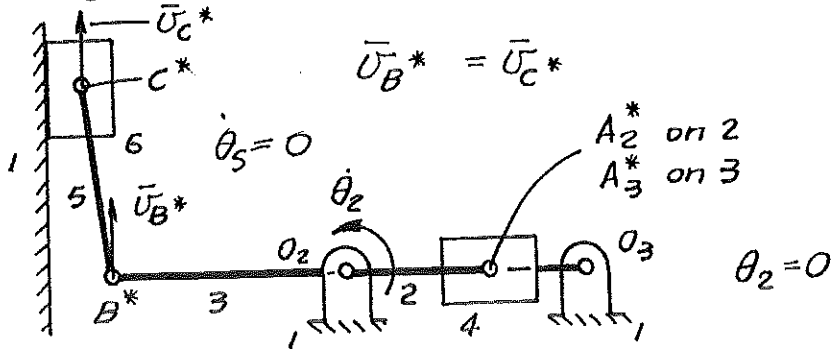
(a) geometries for which velocity of link 6 is zero (i.e., limit positions)



$$\theta_2^{(1)} = \cos^{-1}\left(r_{A_2O_2} / r_{O_2O_3} \right) = \cos^{-1}(3.0/5.0) = 53.1^\circ$$

$$\theta_2^{(2)} = 360^\circ - \theta_2^{(1)} = 306.9^\circ$$

(b) $\bar{v}_B$ and $\bar{v}_C$ have the same direction



$$v_{A_2^*} = r_{A_2O_2} |\dot{\theta}_2| = r_{A_3^*O_3} |\dot{\theta}_3|, \quad |\dot{\theta}_3| = \frac{r_{A_2O_2}}{r_{A_3^*O_3}} |\dot{\theta}_2|$$

$$|\bar{v}_C^*| = |\bar{v}_B^*| = r_{B^*O_3} |\dot{\theta}_3| = r_{B^*O_3} \frac{r_{A_2O_2}}{r_{A_3^*O_3}} |\dot{\theta}_2|$$

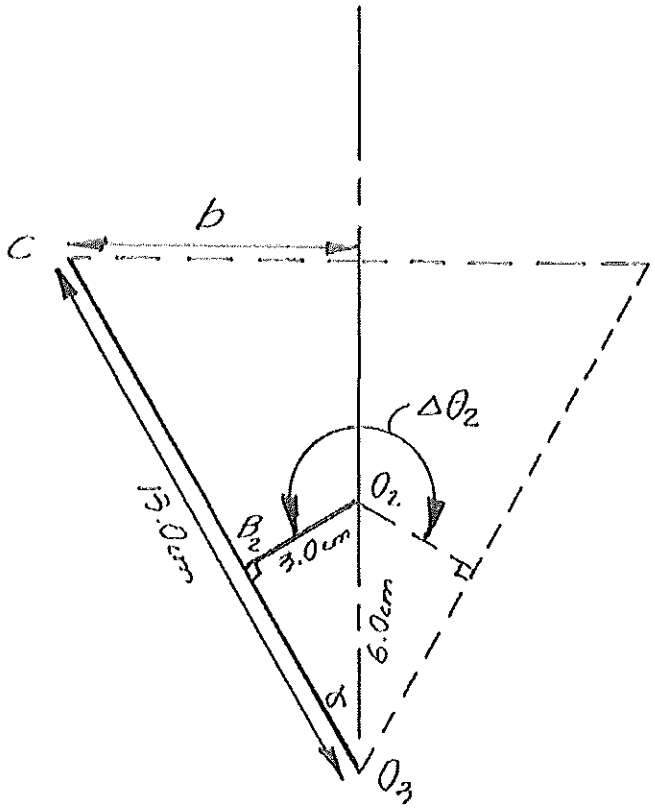
$$= 10.0 \times \frac{3.0}{5.0 - 3.0} \times 10.0 = 150 \frac{cm}{sec}$$

similarly at $\theta_2 = 180^\circ$, $|\bar{v}_C^*| = |\bar{v}_B^*| = 37.5 \frac{cm}{sec}$

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P2.6

limit geometries:



$$\alpha = \sin^{-1}\frac{3.0}{6.0} = 30°$$

$$b = 13.0 \times \sin 30°$$
$$= 6.5\,cm$$

(a) stroke = $2b$ = 13.0 cm

(b) $\theta_2^{(1)} = 180° + \alpha = 210°$

$\theta_2^{(2)} = 360° - \alpha = 330°$

(c) $\theta_2 =$ 90° or 270° When link 5 is in pure translation

also $\theta_2 =$ 210° or 330° When $\dot{\theta}_3 = 0$ & $\dot{\theta}_5 = 0$

P2.6 CONTINUED

(d) motion to left requires 120° rotation of link 2

$$|\dot{\theta}_2| = 8.0 \frac{rad}{sec} \times \frac{180^\circ}{\pi\ rad} = 458^\circ/sec$$

$$\therefore \text{time taken} = \frac{120^\circ}{458^\circ/sec} = 0.262\ sec$$

$$\therefore \text{average speed to left} = \frac{\text{stroke}}{\text{time taken}}$$

$$= \frac{13.0\ cm}{0.262\ sec} = \underline{49.7\ \frac{cm}{sec}}$$

(e) motion to right requires 240° rotation of link 2

$$\text{time taken } \frac{240^\circ}{458^\circ/sec} = 0.524\ sec$$

$$\therefore \text{average speed to the right} = \frac{\text{stroke}}{\text{time taken}}$$

$$= \frac{13.0\ cm}{0.524\ sec} = \underline{24.8\ \frac{cm}{sec}}$$

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P2.7

$r_1 = 8.0\,cm$; $r_2 = 2.0\,cm$; $r_3 = 4.0\,cm$; $r_4 = 7.0\,cm$

$\dot{\theta}_2 = 40.0\ \frac{rad}{sec}$ CW

$$\alpha_1 = \cos^{-1}\left[\frac{r_1^2 + (r_2+r_3)^2 - r_4^2}{2(r_2+r_3)\,r_1}\right] = 57.9^\circ$$

$$\alpha_2 = \cos^{-1}\left[\frac{r_1^2 + (r_3-r_2)^2 - r_4^2}{2(r_3-r_2)\,r_1}\right] = 53.6^\circ$$

$$\beta_1 = \cos^{-1}\left[\frac{r_1^2 - (r_2+r_3)^2 + r_4^2}{2\,r_1\,r_4}\right] = 46.6^\circ$$

$$\beta_2 = \cos^{-1}\left[\frac{r_1^2 - (r_3-r_2)^2 + r_4^2}{2\,r_1\,r_4}\right] = 13.3^\circ$$

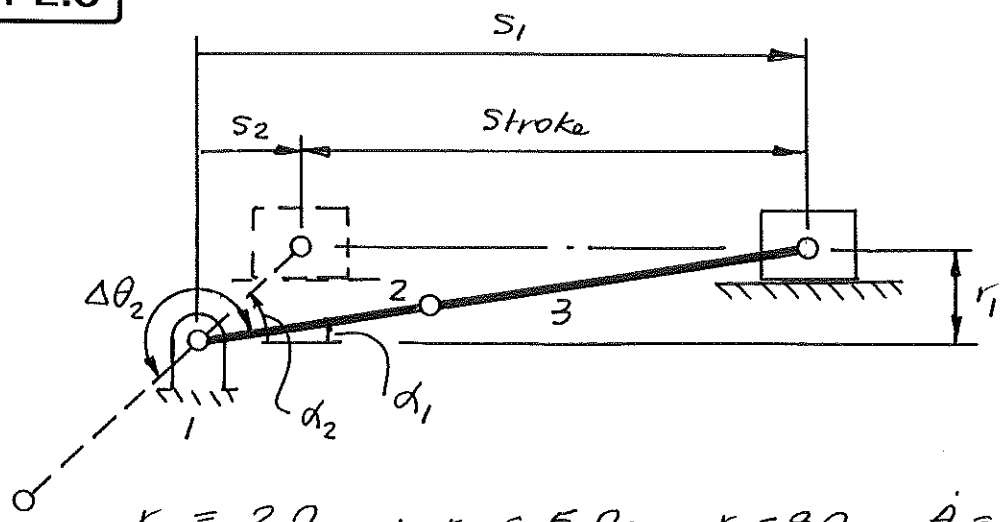
$\Delta\theta_2 = 180^\circ + \alpha_2 - \alpha_1 = 175.7^\circ$; $\Delta\theta_4 = \beta_1 - \beta_2 = 33.3^\circ$

(a) $$(\dot{\theta}_{4\,avg})_{CW} = \frac{\Delta\theta_4}{(\Delta\theta_2 / \dot{\theta}_2)} = 7.58\ \frac{rad}{sec}$$

(b) $$(\dot{\theta}_{4\,avg})_{CCW} = \frac{\Delta\theta_4}{\left(\frac{2\pi - \Delta\theta_2}{\dot{\theta}_2}\right)} = 7.22\ \frac{rad}{sec}$$

(c) $$T_R = \frac{2\pi - \Delta\theta_2}{\Delta\theta_2} = 1.05$$

P2.8



$r_1 = 2.0\,cm$; $r_2 = 5.0\,cm$, $r_3 = 8.0\,cm$, $\dot{\theta}_2 = 30\ \frac{rad}{sec}$ CCW

$$\alpha_1 = \sin^{-1}\left(\frac{r_1}{r_2+r_3}\right) = \sin^{-1}\left(\frac{2.0}{5.0+8.0}\right) = 8.8°$$

$$\alpha_2 = \sin^{-1}\left(\frac{r_1}{r_3-r_2}\right) = 41.8°$$

$$\Delta\theta_2 = 180° + \alpha_2 - \alpha_1 = 213° = 3.72\ rad$$

$$s_1 = \left[(r_2+r_3)^2 - r_1^2\right]^{1/2} = \left[(5.0+8.0)^2 - 2.0^2\right]^{1/2} = 12.85\,cm$$

$$s_2 = \left[(r_3-r_2)^2 - r_1^2\right]^{1/2} = 2.24\,cm$$

$$Stroke = s_1 - s_2 = 12.85 - 2.24 = 10.61\,cm$$

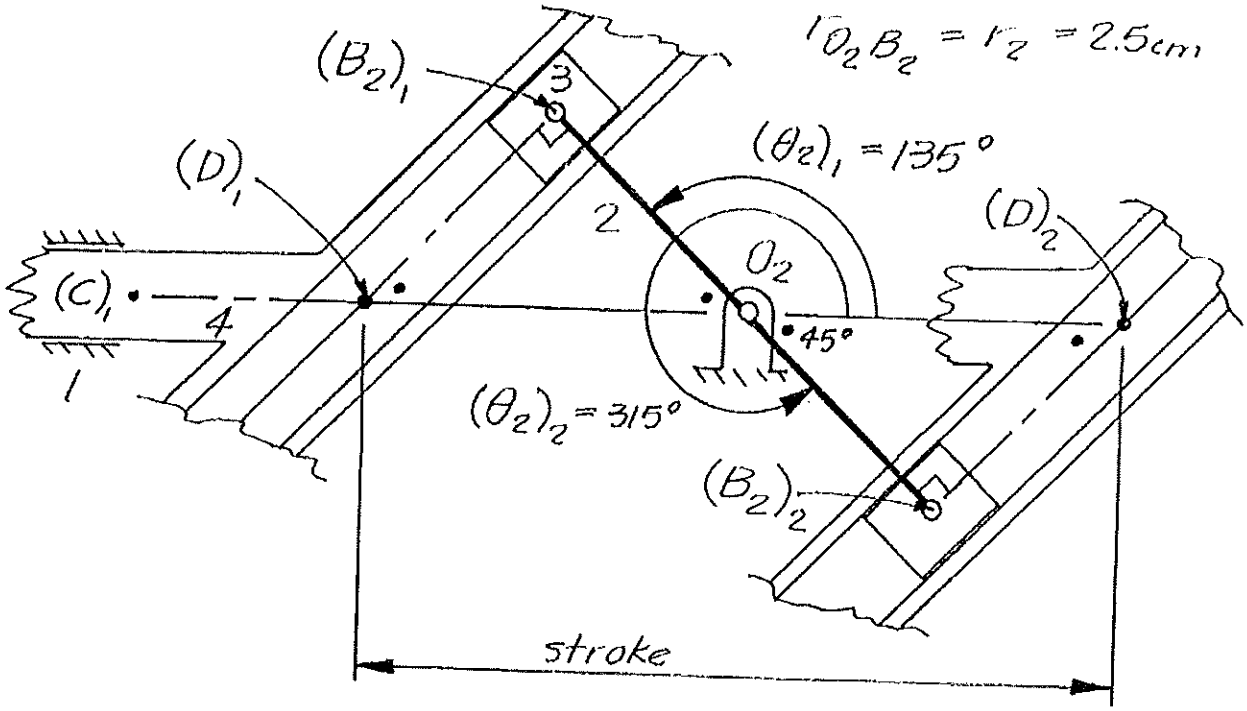
(a) $$(\bar{v}_{4,avg})_{right} = \frac{Stroke}{\left(\frac{2\pi - \Delta\theta_2}{\dot{\theta}_2}\right)} = 124\ \frac{cm}{sec}$$

(b) $$(\bar{v}_{4,avg})_{left} = \frac{Stroke}{\Delta\theta_2 / \dot{\theta}_2} = 85.6\ \frac{cm}{sec}$$

(c) $$T_R = \frac{\Delta\theta_2}{2\pi - \Delta\theta_2} = 1.45$$

P2.9

(a) limit geometries of mechanism (i.e., $v_C = 0$)



values of θ_2 when point C is stationary:

$135°$ & $315°$

(b) stroke of C = stroke of D

$$= 2\{2[r_2 \cos 45°]\} = 7.07\text{cm}$$

P2.9 CONTINUED

(c) time to move between limit positions :

$$\Delta t = \frac{\Delta\theta_2}{\dot{\theta}_2} = \frac{\pi \text{ rad}}{8 \frac{\text{rad}}{\text{sec}}} = 0.393 \text{ sec}$$

$$\therefore \underline{\text{average speed to the left}} = \frac{\text{stroke}}{\Delta t}$$

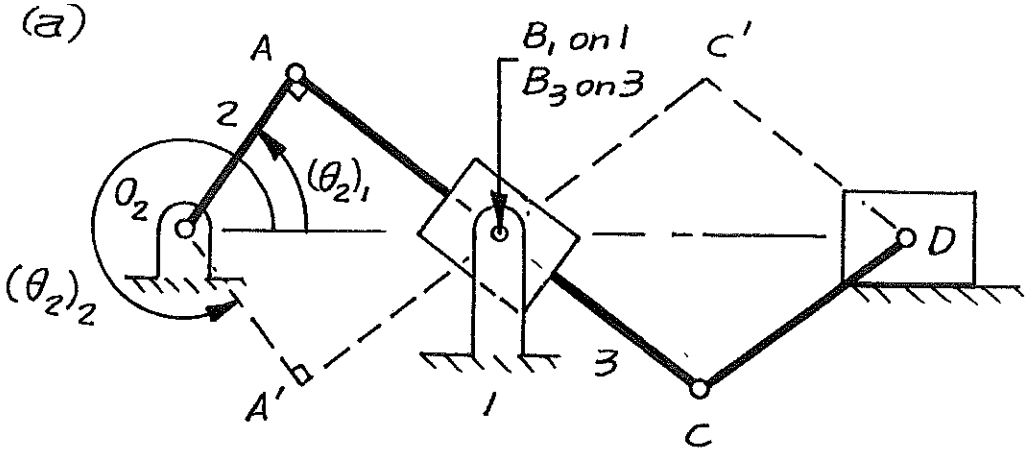
$$= \frac{7.07 \text{ cm}}{0.393 \text{ sec}} = 18.0 \frac{\text{cm}}{\text{sec}}$$

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P2.10

$r_{O_2A} = 3.0\text{cm}$; $r_{O_2B_1} = 5.0\text{cm}$; $r_{AC} = 8.0\text{cm}$; $r_{CD} = 4.0\text{cm}$

(a)



$\dot{\theta}_3 = 0$ when link 2 is perpendicular to link 3

$$(\theta_2)_1 = \tan^{-1}\left\{\frac{r_{AB_3}}{r_{O_2A}}\right\} = \tan^{-1}\left\{\frac{\left[(r_{O_2B_3})^2 - (r_{O_2A})^2\right]^{\frac{1}{2}}}{r_{O_2A}}\right\}$$

$$= \tan^{-1}\left\{\frac{[5.0^2 - 3.0^2]^{1/2}}{3.0}\right\} = 53.1^\circ$$

$$(\theta_2)_2 = 360^\circ - (\theta_2)_1 = 306.9^\circ$$

(b) $v_D = 0$ when mechanism is in limit positions (i.e., $\theta_2 = 0, 180^\circ$)

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P2.10 CONTINUED

(c) $|a^c_{B_1 B_3}| = |2 \dot{r}_{B_1 B_3} \dot{\theta}_3|$

$a^c_{B_1 B_3} = 0$ when $\dot{r}_{B_1 B_3} = 0$ OR $\dot{\theta}_3 = 0$.

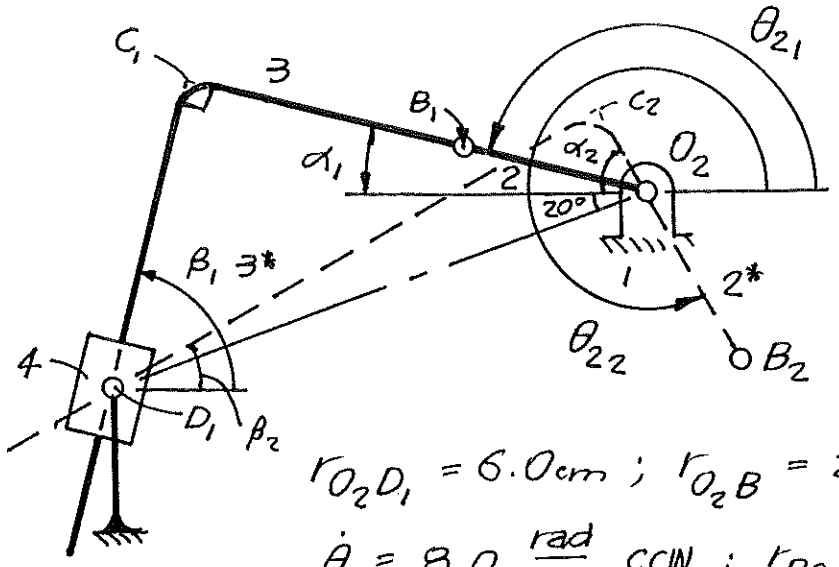
∴ the corresponding values of θ_2 are

0, 53.1°, 180°, 306.9°

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P2.11

(a)



$r_{O_2D_1} = 6.0\text{cm}$; $r_{O_2B} = 2.0\text{cm}$

$\dot{\theta}_2 = 8.0 \frac{\text{rad}}{\text{sec}}$ CCW ; $r_{BC} = 3.0\text{cm}$

$$\alpha_1 + 20^\circ = \cos^{-1}\left(\frac{5.0}{6.0}\right) = 33.6^\circ,$$

$$\therefore \underline{\theta_{21}} = 180^\circ - 33.6^\circ + 20^\circ = \underline{166.4^\circ}$$

$$\alpha_2 + 20^\circ = \cos^{-1}\left(\frac{1.0}{6.0}\right) = 80.4^\circ$$

$$\therefore \underline{\theta_{22}} = 360^\circ - 80.4^\circ + 20^\circ = \underline{299.6^\circ}$$

(b) triangle $D_1 C_1 O_2$:

$$(\beta_1 - 20^\circ) + \underset{33.6^\circ}{\cancel{\alpha_1 + 20^\circ}} + 90^\circ = 180^\circ \; ; \; \beta_1 = 76.4^\circ$$

triangle $D_1 C_2 O_2$:

$$(\beta_2 - 20^\circ) + \underset{80.4^\circ}{\cancel{\alpha_2 + 20^\circ}} + 90^\circ = 180^\circ \; ; \; \beta_2 = 29.6^\circ$$

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P2.11 CONTINUED

(b) between θ_{2_1} & θ_{2_2} link 4 rotates CW

$$\Delta t = \frac{(\theta_{2_2} - \theta_{2_1})}{\dot{\theta}_2} = \frac{299.6^\circ - 166.4^\circ}{8.0} \times \frac{\pi}{180}$$

$$= 0.291 \text{ sec}$$

$$(\dot{\theta}_{4,avg})_{CW} = \left|\frac{\beta_2 - \beta_1}{\Delta t}\right| = \left|\frac{29.6^\circ - 76.4^\circ}{0.291 \text{sec}} \times \frac{\pi}{180}\right|$$

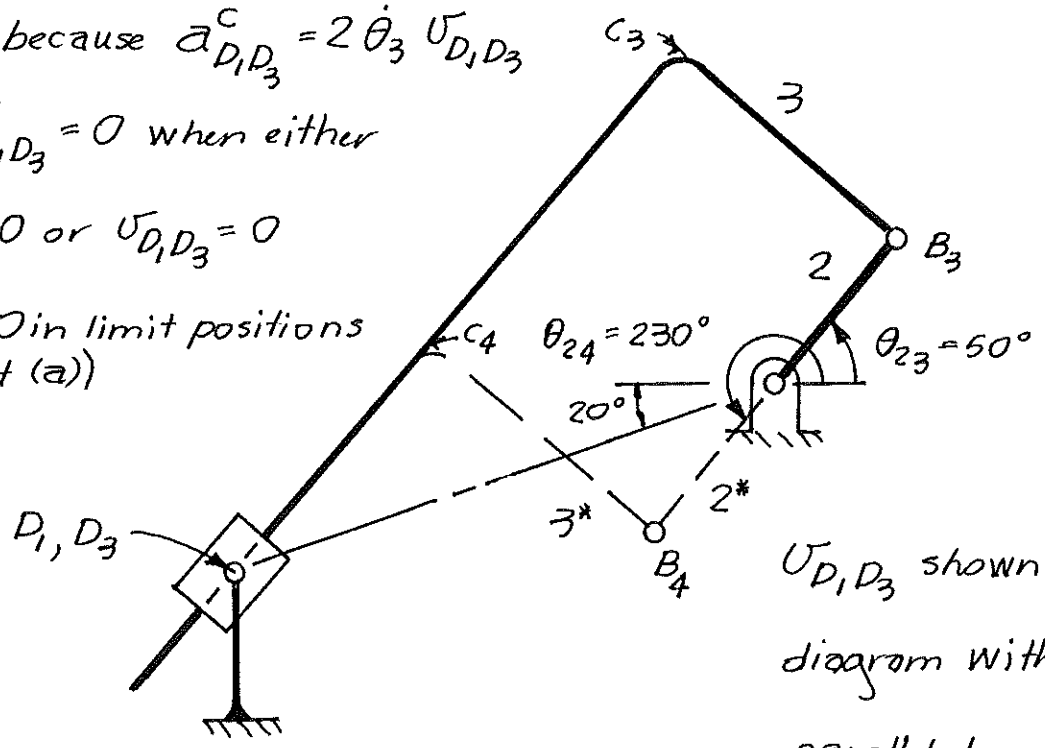
$$= \left|-2.81 \frac{rad}{sec}\right|; \quad \underline{(\dot{\theta}_{4,avg})_{CW} = 2.81 \frac{rad}{sec}}$$

(c) because $a^c_{D_1D_3} = 2\dot{\theta}_3 v_{D_1D_3}$

$\therefore a^c_{D_1D_3} = 0$ when either

$\dot{\theta}_3 = 0$ or $v_{D_1D_3} = 0$

$\dot{\theta}_3 = 0$ in limit positions (part (a))



$v_{D_1D_3}$ shown in diagram with O_2B parallel to D_1C

complete set of values when $a^c_{D_1D_3} = 0$:

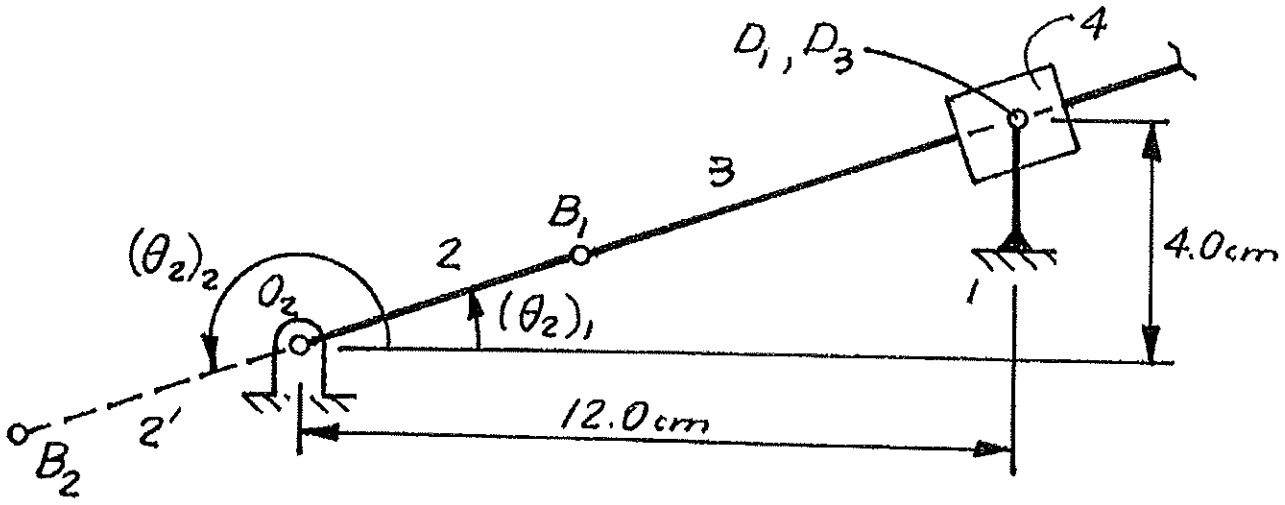
$\underline{\theta_2 = 50^\circ, 166.4^\circ, 230^\circ, 299.6^\circ}$

P2.12

(a) since $a^c_{D_1D_3} = 2\dot{r}_{D_1D_3}\dot{\theta}_3$, then

$a^c_{D_1D_3} = 0$ when:

(i) $\dot{r}_{D_1D_3} = 0$ (i.e, limit positions)



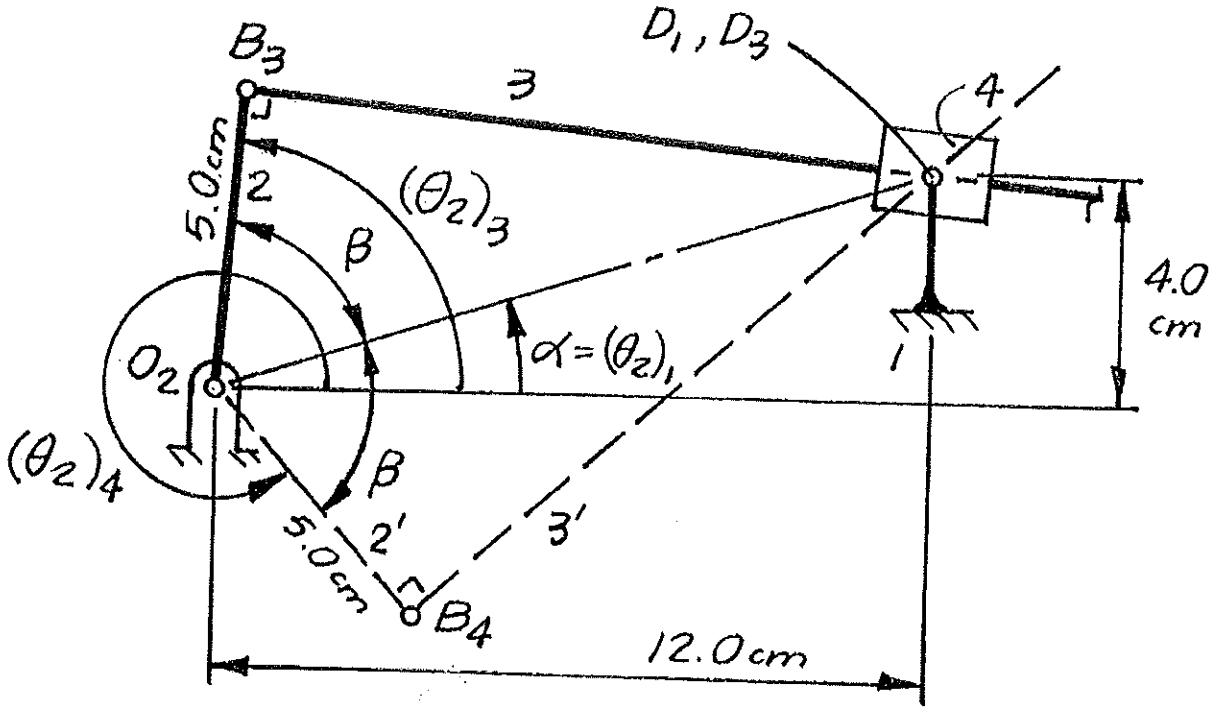
$$(\theta_2)_1 = \tan^{-1}\left(\frac{4.0}{12.0}\right) = 18.4°$$

$$(\theta_2)_2 = 180° + (\theta_2)_1 = 198.4°$$

and ...

P2.12 CONTINUED

(ii) $\dot{\theta}_3 = 0$ (i.e., pure translation of link 3)



$$r_{O_2 D_1} = (12.0^2 + 4.0^2)^{1/2} = 12.65 \text{ cm}$$

$$\beta = \cos^{-1}\left(\frac{r_{O_2 B_3}}{r_{O_2 D_1}}\right) = 66.7^\circ$$

$$(\theta_2)_3 = \alpha + \beta = 85.1^\circ$$

$$(\theta_2)_4 = 360^\circ - \beta + \alpha = 311.7^\circ$$

complete set of values of θ_2 when $a^C_{D_1 D_3} = 0$:

$$18.4^\circ, \quad 85.2^\circ, \quad 198.4^\circ, \quad 311.7^\circ$$

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P2.13

$r_1 = 10\,cm$; $r_2 = 4.0\,cm$

$r_3 = 12\,cm$; $r_4 = 8.0\,cm$

$$\underline{\phi_{min}} = \cos^{-1}\left[\frac{r_3^2 + r_4^2 - (r_1 - r_2)^2}{2 r_3 r_4}\right] \underline{= 26.4^\circ}$$

$$\underline{\phi_{max}} = \cos^{-1}\left[\frac{r_3^2 + r_4^2 - (r_1 + r_2)^2}{2 r_3 r_4}\right] \underline{= 86.4^\circ}$$

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P2.14

$r_1 = 2.0\ cm$; $r_2 = 4.0\ cm$; $r_3 = 12\ cm$

$$\phi_{min} = \cos^{-1}\left[\frac{r_2 - r_1}{r_3}\right] = 80.4^\circ$$

$$\phi_{max} = \cos^{-1}\left[\frac{-r_2 - r_1}{r_3}\right] = 120^\circ$$

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P2.15

$r_1 = 10\,cm$; $r_2 = 2.0\,cm$

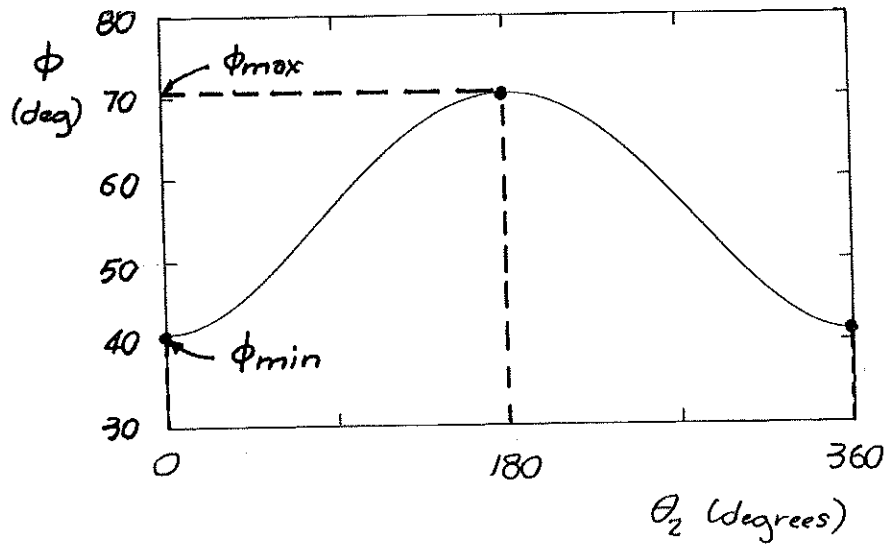
$r_3 = 12\,cm$; $r_4 = 8.0\,cm$

$$r_{BO_4}^2 = r_1^2 + r_2^2 - 2 r_1 r_2 \cos\theta_2$$

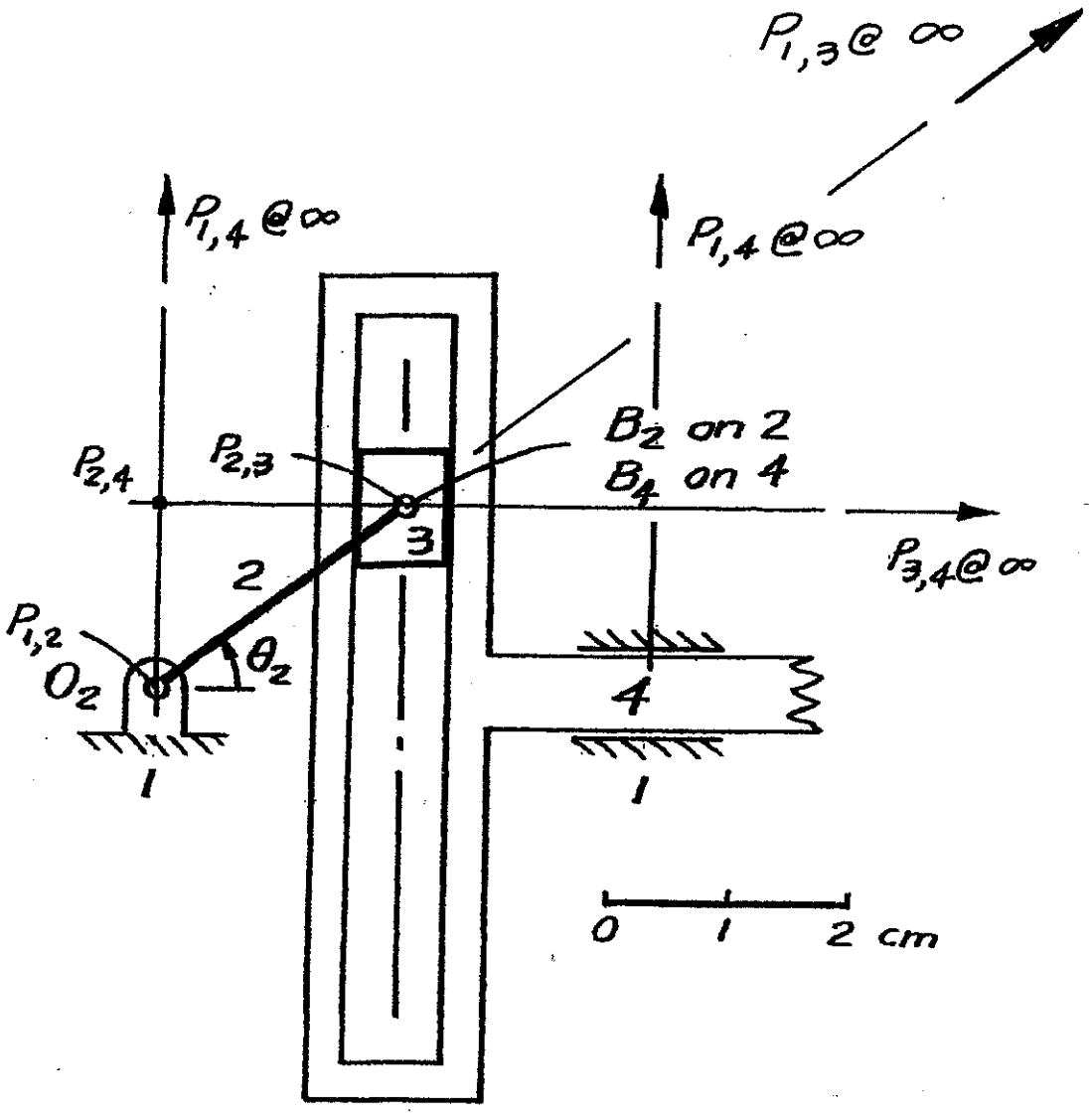
$$\phi = \cos^{-1}\left[\frac{r_3^2 + r_4^2 - r_{BO_4}^2}{2 r_3 r_4}\right]$$

$$\phi_{min} = \cos^{-1}\left[\frac{r_3^2 + r_4^2 - (r_1 - r_2)^2}{2 r_3 r_4}\right] = 41.4^\circ$$

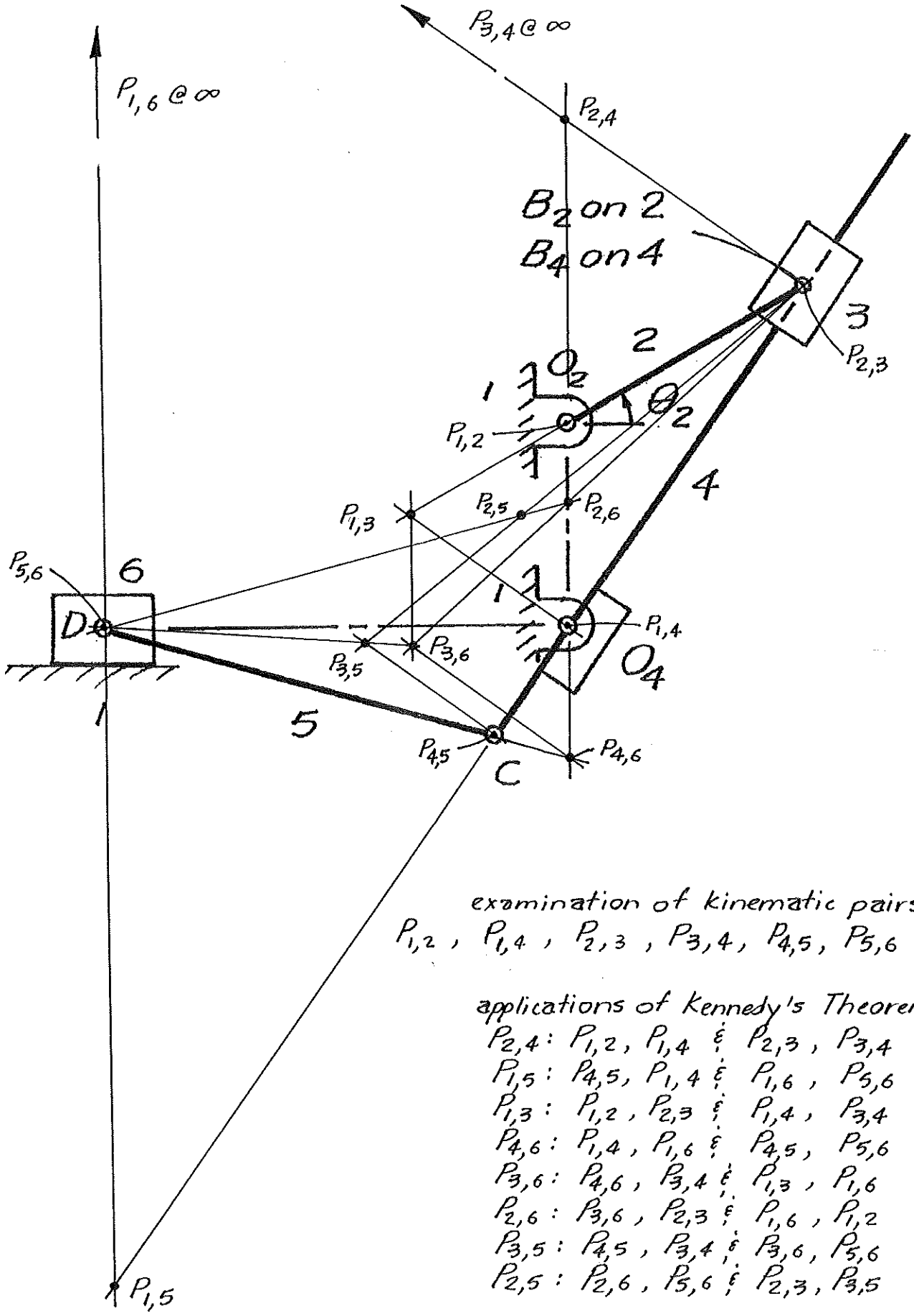
$$\phi_{max} = \cos^{-1}\left[\frac{r_3^2 + r_4^2 - (r_1 + r_2)^2}{2 r_3 r_4}\right] = 70.5^\circ$$



P2.16



P2.17



examination of kinematic pairs:

$P_{1,2}$, $P_{1,4}$, $P_{2,3}$, $P_{3,4}$, $P_{4,5}$, $P_{5,6}$, $P_{1,6}$

applications of Kennedy's Theorem:

$P_{2,4}$: $P_{1,2}$, $P_{1,4}$ & $P_{2,3}$, $P_{3,4}$

$P_{1,5}$: $P_{4,5}$, $P_{1,4}$ & $P_{1,6}$, $P_{5,6}$

$P_{1,3}$: $P_{1,2}$, $P_{2,3}$ & $P_{1,4}$, $P_{3,4}$

$P_{4,6}$: $P_{1,4}$, $P_{1,6}$ & $P_{4,5}$, $P_{5,6}$

$P_{3,6}$: $P_{4,6}$, $P_{3,4}$ & $P_{1,3}$, $P_{1,6}$

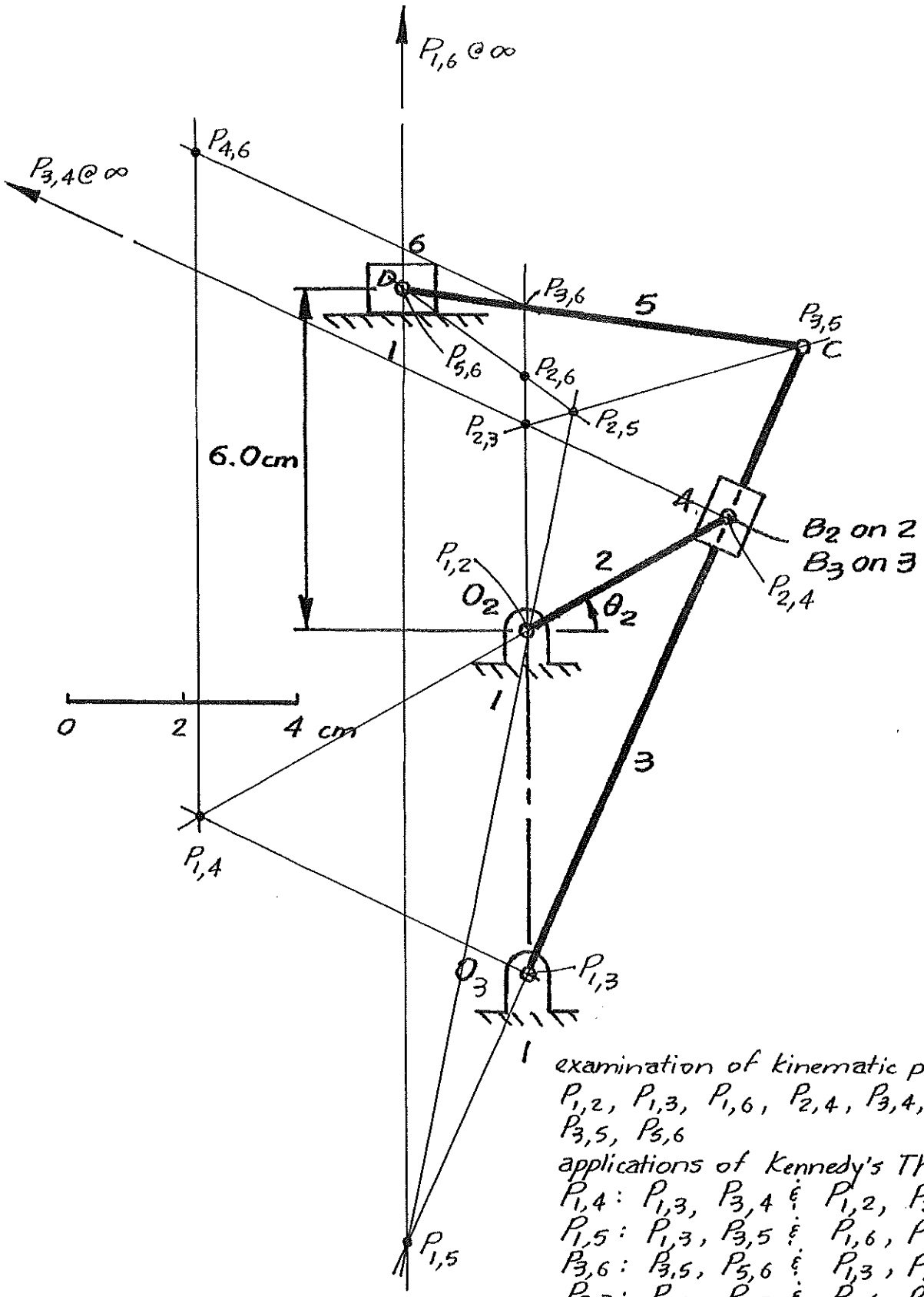
$P_{2,6}$: $P_{3,6}$, $P_{2,3}$ & $P_{1,6}$, $P_{1,2}$

$P_{3,5}$: $P_{4,5}$, $P_{3,4}$ & $P_{3,6}$, $P_{5,6}$

$P_{2,5}$: $P_{2,6}$, $P_{5,6}$ & $P_{2,3}$, $P_{3,5}$

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P2.18

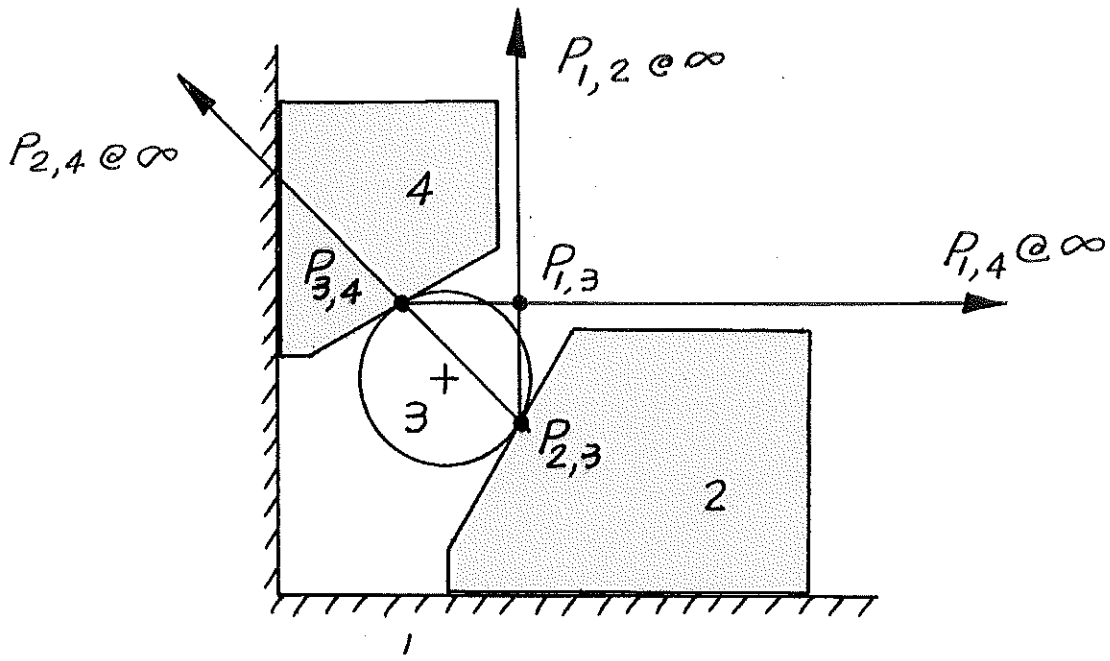


examination of kinematic pairs:
$P_{1,2}$, $P_{1,3}$, $P_{1,6}$, $P_{2,4}$, $P_{3,4}$, $P_{3,5}$, $P_{5,6}$

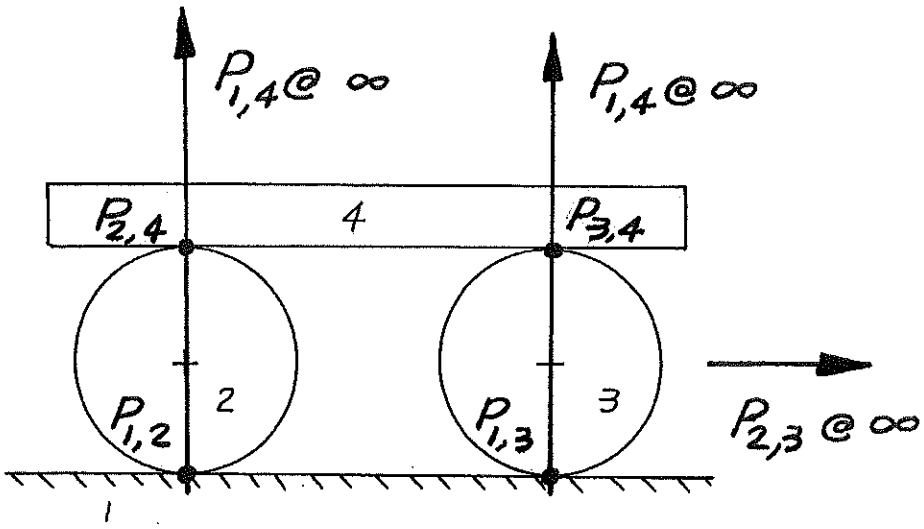
applications of Kennedy's Theorem:

$P_{1,4}$: $P_{1,3}$, $P_{3,4}$ & $P_{1,2}$, $P_{2,4}$
$P_{1,5}$: $P_{1,3}$, $P_{3,5}$ & $P_{1,6}$, $P_{5,6}$
$P_{3,6}$: $P_{3,5}$, $P_{5,6}$ & $P_{1,3}$, $P_{1,6}$
$P_{2,3}$: $P_{1,2}$, $P_{1,3}$ & $P_{2,4}$, $P_{3,4}$
$P_{4,6}$: $P_{1,4}$, $P_{1,6}$ & $P_{3,4}$, $P_{3,6}$
$P_{2,5}$: P_{23}, $P_{3,5}$ & $P_{1,2}$, $P_{1,5}$
$P_{2,6}$: $P_{2,5}$, $P_{5,6}$ & $P_{1,2}$, $P_{1,6}$

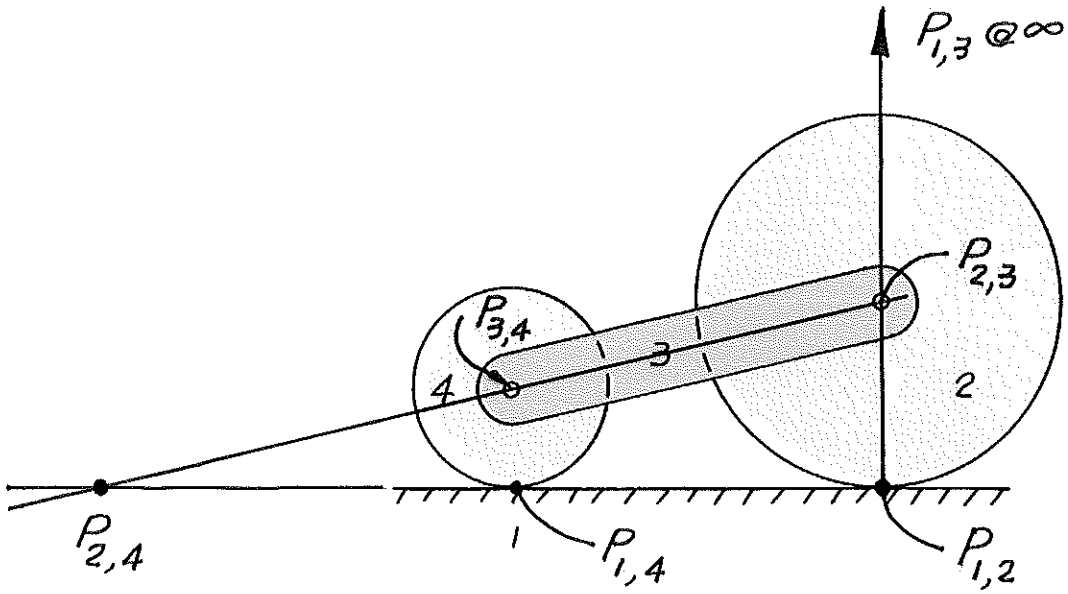
P2.19



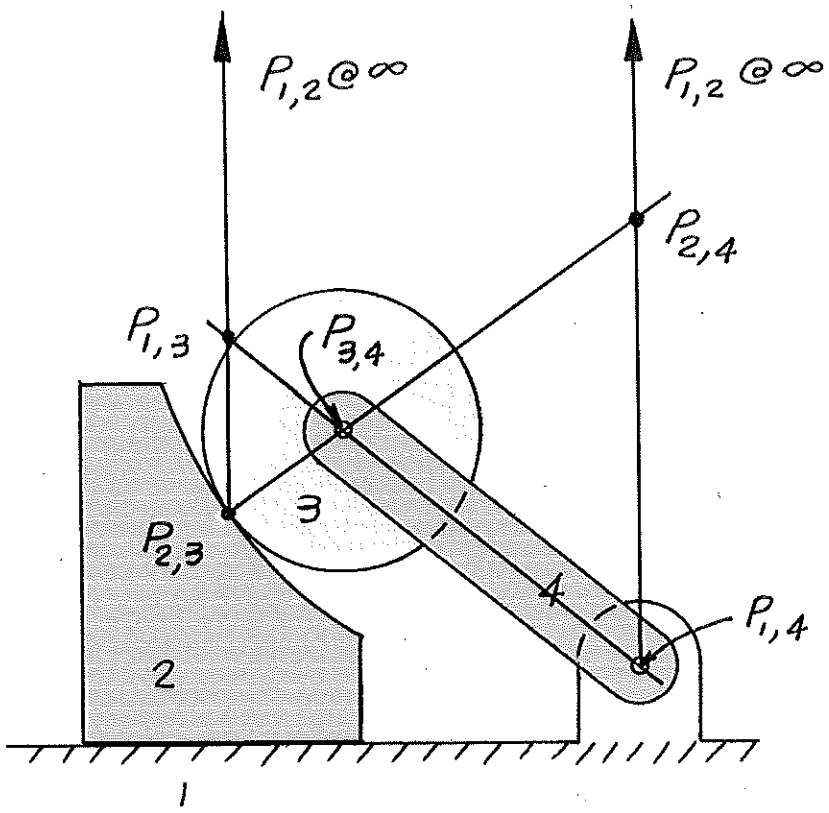
P2.20



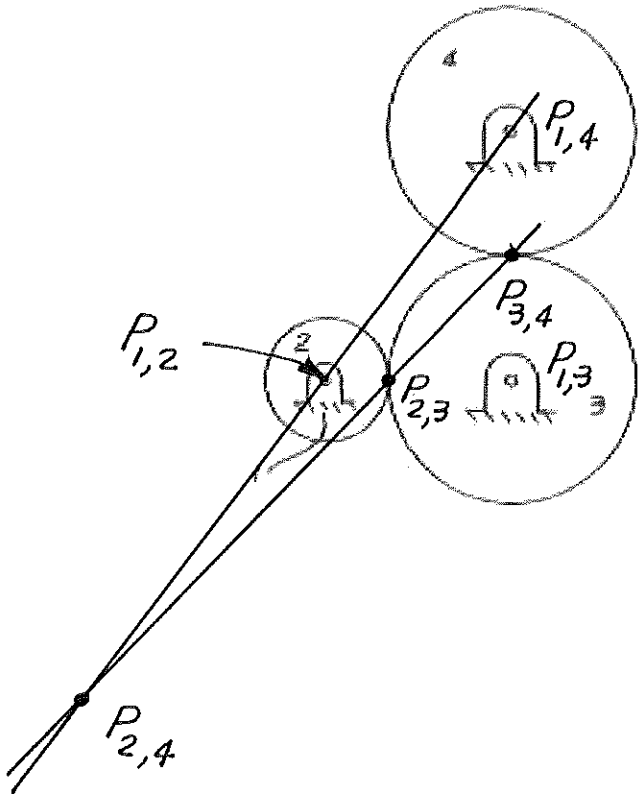
P2.21

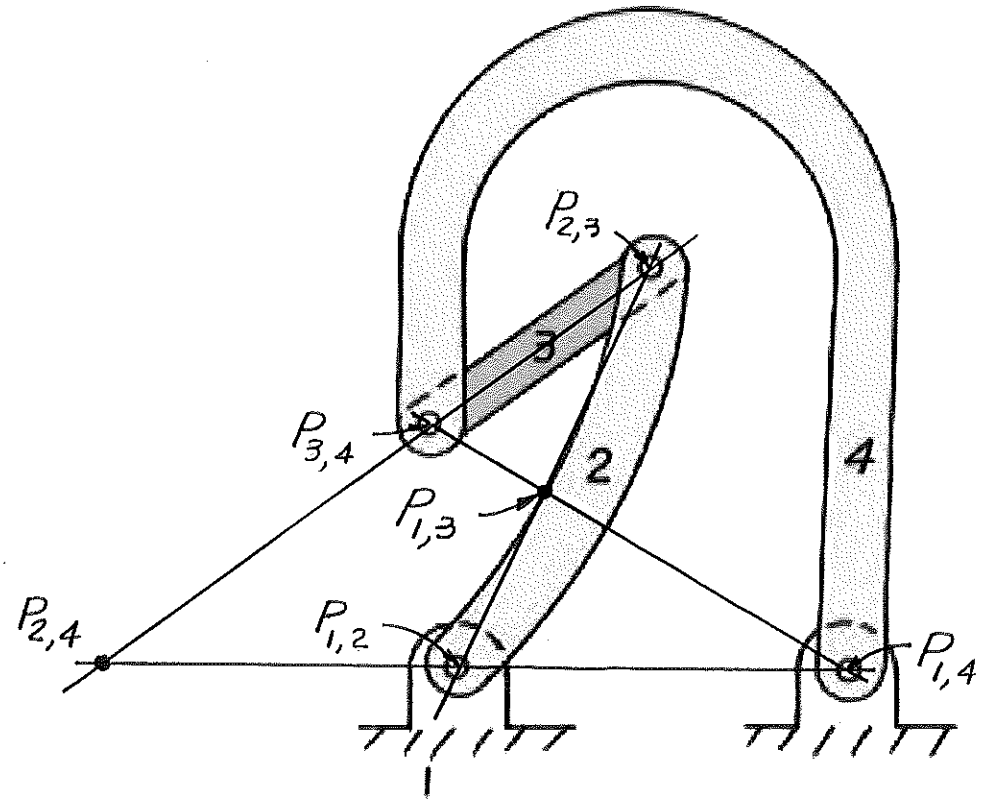


P2.22

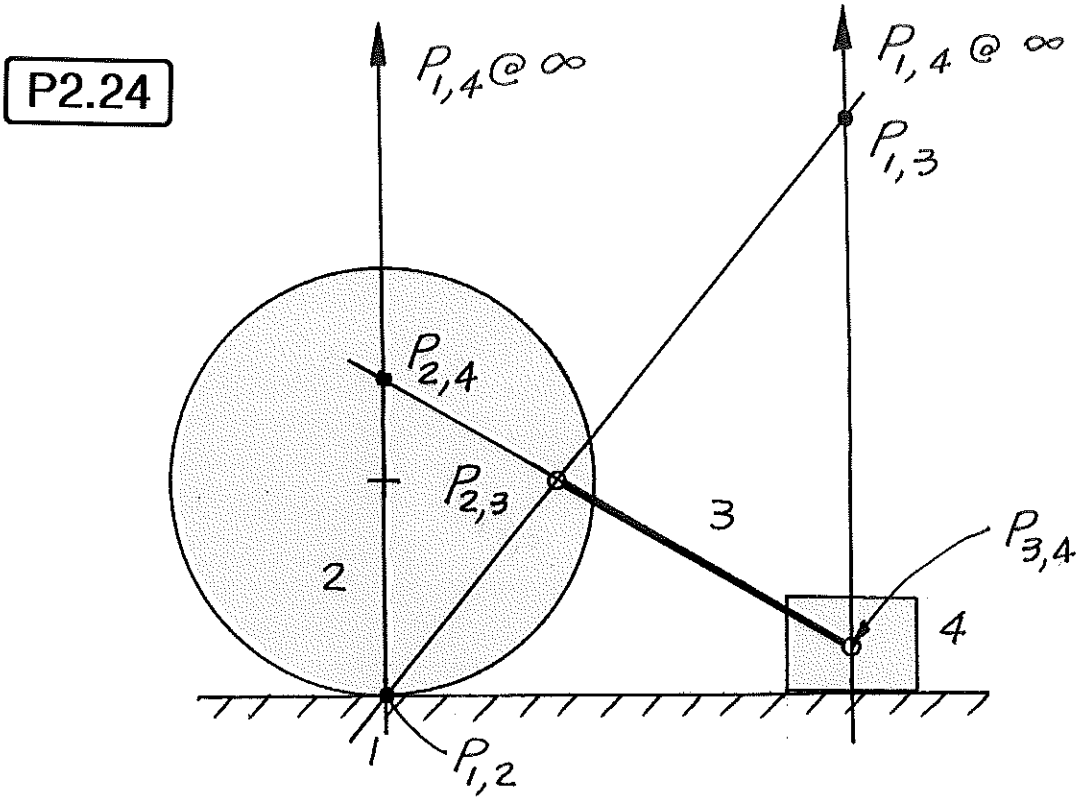


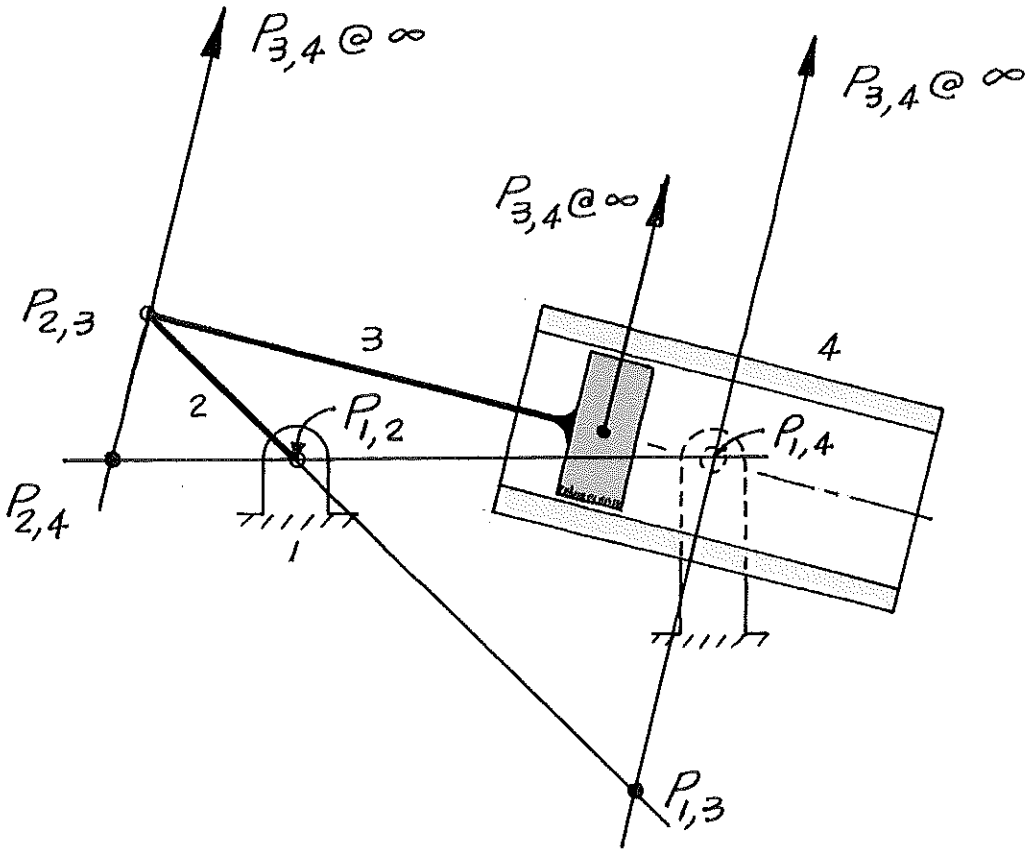
P2.23



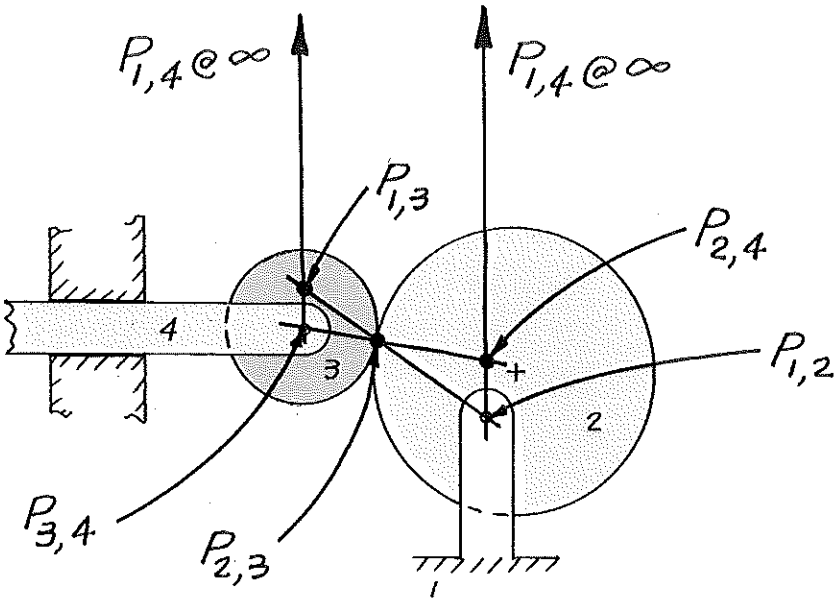


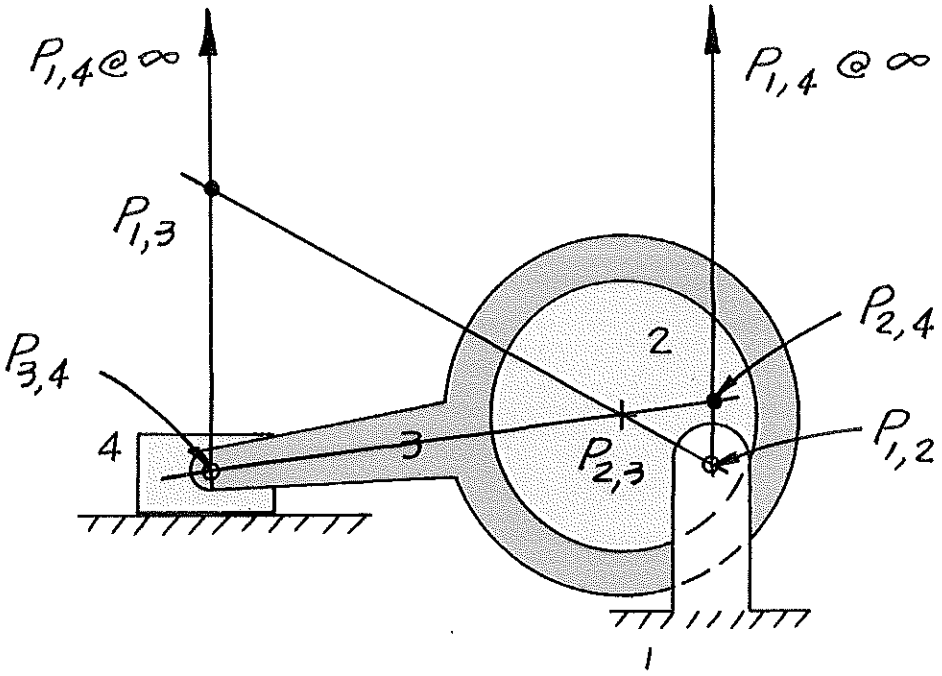
P2.24


P1,4 @ ∞
P1,4 @ ∞
P1,3
P2,4
P2,3
3
P3,4
2
4
1
P1,2


P3,4 @ ∞
P3,4 @ ∞
P3,4 @ ∞
P2,3
3
4
2
P1,2
P1,4
P2,4
1
P1,3

P2.25


P1,4@∞
P1,4@∞
P1,3
P2,4
P1,2
4
3
2
P3,4
P2,3
1


P1,4@∞
P1,4@∞
P1,3
P2,4
P3,4
2
4
3
P2,3
P1,2
1

P2.26

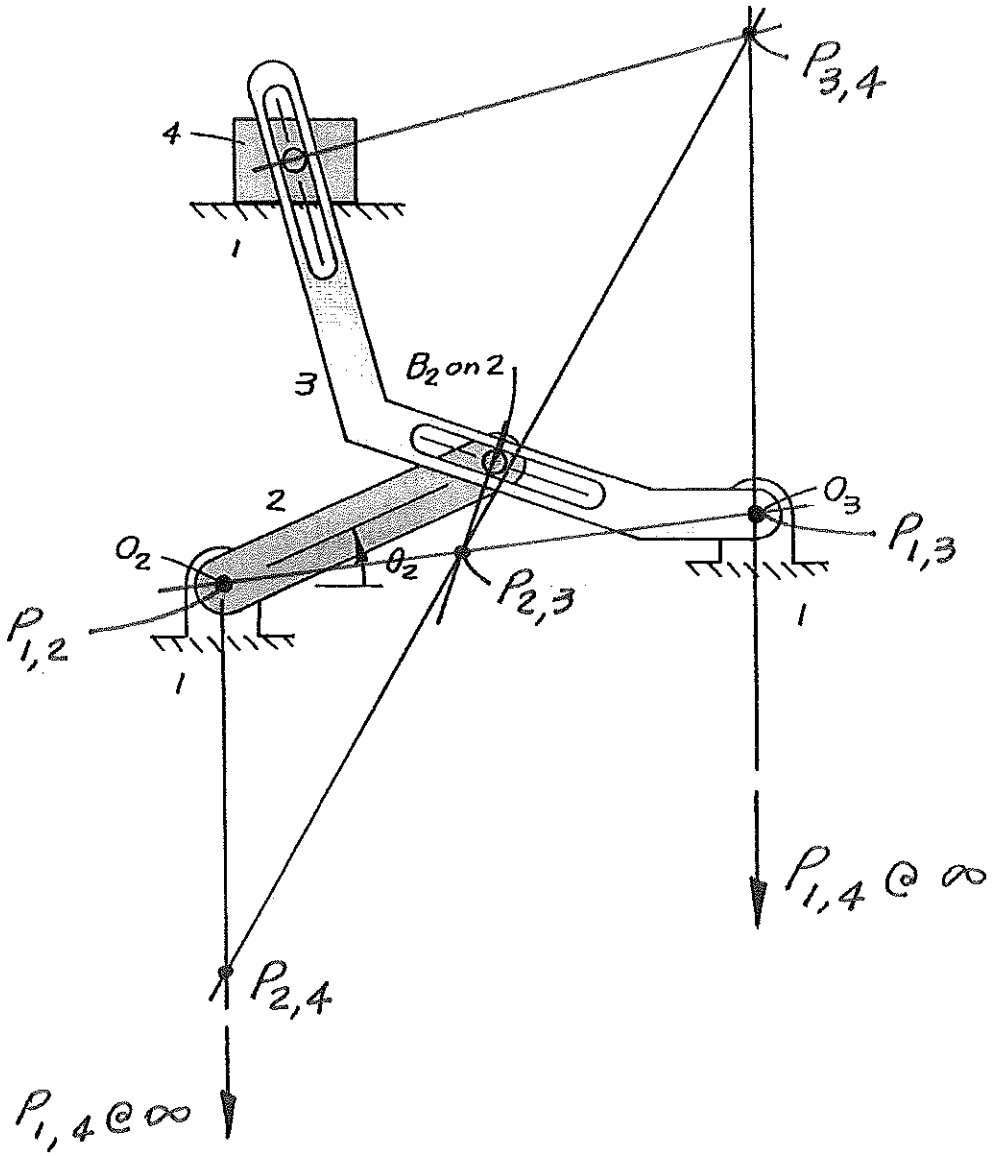
(a) $n = 4$

turning pairs: 2
sliding pairs: 1
$\Big\} j_1 = 2 + 1 = 3$

two degree of freedom pairs: 2, $j_2 = 2$

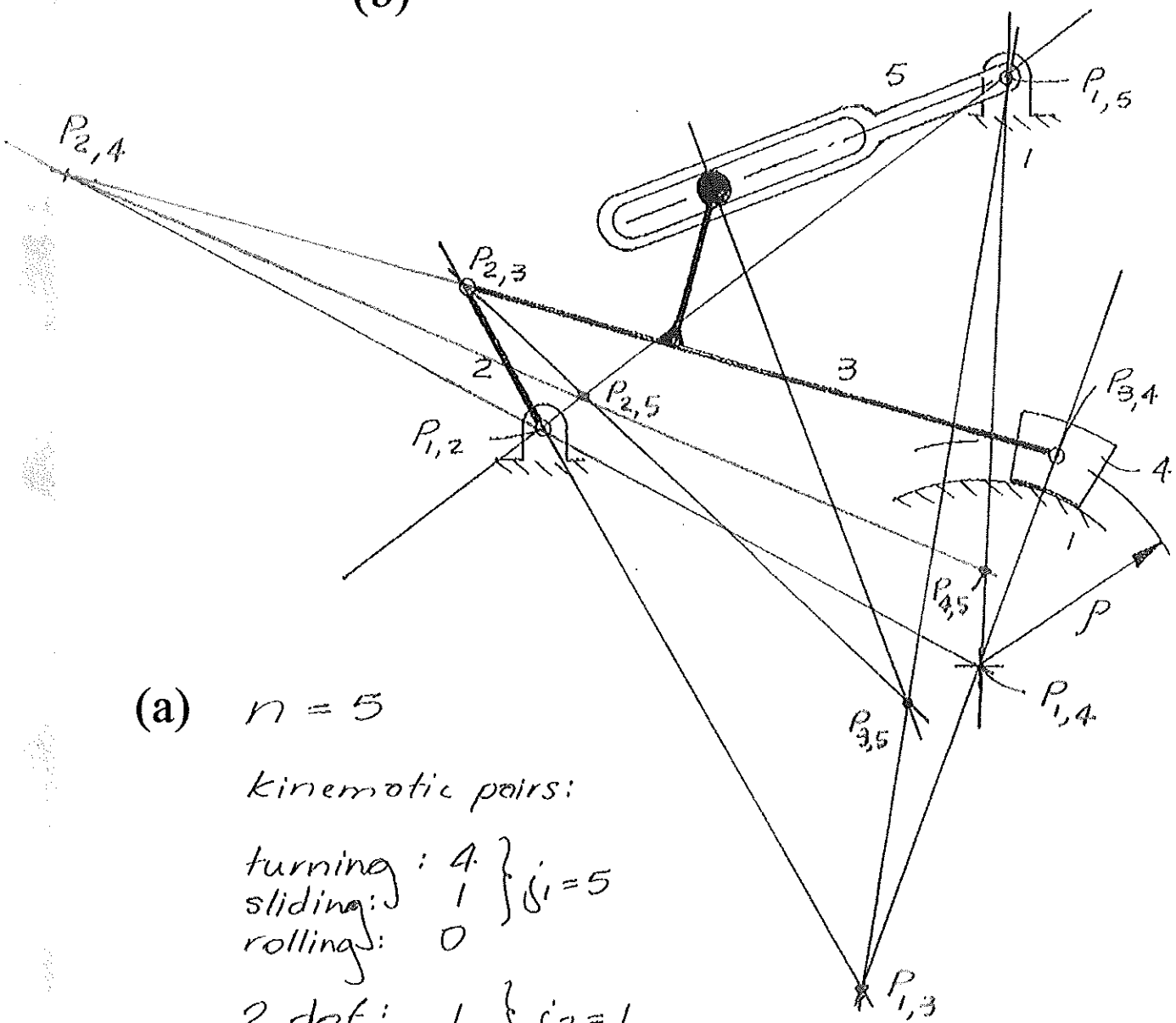
$$m = 3(n-1) - 2j_1 - j_2 = 3(4-1) - 2\times 3 - 2 = 1$$

(b)



P2.27

(b)



(a) $n = 5$

kinematic pairs:

turning: 4
sliding: 1
rolling: 0
} $j_1 = 5$

2 dof: 1 } $j_2 = 1$

mobility:

$m = 3(n-1) - 2j_1 - j_2$

$= 3(5-1) - 2\times 5 - 1 = 1$

P2.28

(a) kinematic pairs:

- sliding: 1
- turning: 3
- rolling: 0

$\Big\}\ j_1 = 1 + 3 + 0 = 4$

- 2 dof: 3 ; $j_2 = 3$

no. of links: 5 ; $n = 5$

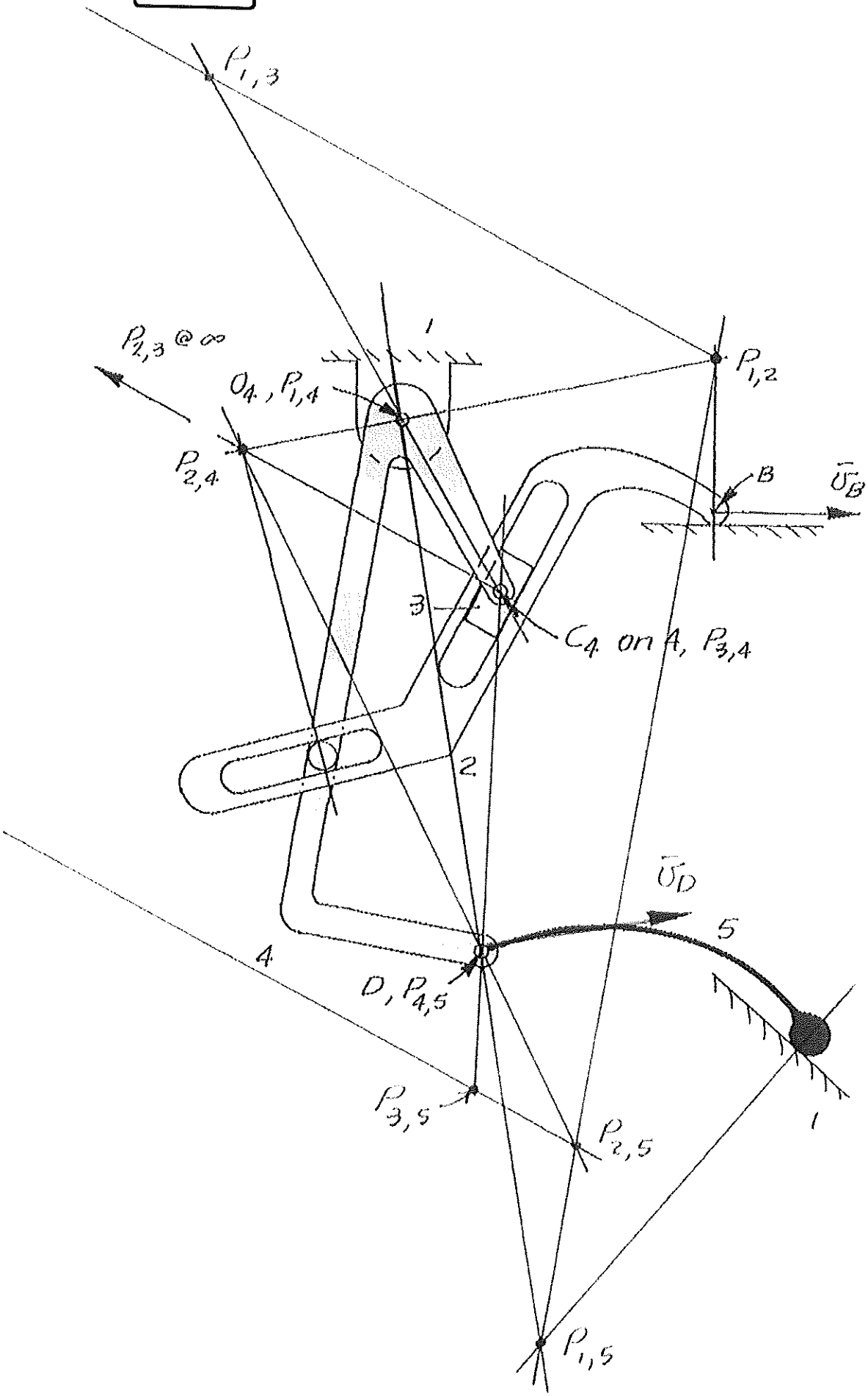
mobility: $m = 3(n-1) - 2j_1 - j_2$

$= 3(5-1) - 2\times 4 - 3 = 1$

(b) see diagram

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P2.28 CONTINUED



P2.29

(a) no. of links : $n = 5$

one degree of freedom pairs:

4 turning

1 sliding

0 rolling $\quad \therefore j_1 = 4 + 1 + 0 = 5$

two degree of freedom pair : 1 , $j_2 = 1$

mobility :

$$\underline{m = 3(n-1) - 2j_1 - j_2 = 1}$$

(b) no. of instantaneous centers : $\frac{n(n-1)}{2} = 10$

(7 instantaneous centers are given)

$\therefore$ no. of instantaneous centers to be found:
$10 - 7 = 3$

- by inspection, instantaneous centers to be found : $P_{1,4}$, $P_{2,5}$, $P_{4,5}$

- see diagram

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P2.29 CONTINUED

