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A Systematic Design Methodology for Geared Robot Manipulators(II)

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ã ê ⊕ ± â å æ ¬ ã Ê ã Sâ þ æ ß ß ß ⁄ ð Ǎ ĵ ñ ß ĝ î µ ÷ ü ã ǎ ß ǔ â ë ü ê å ü â å ð ã Ą æ ß ß ð Ǎ ơ ñ ß ĝ î ó ì Sæ ⁄ ð ê Ą ë ® ä ü æ ä õ ã ü ñ ê â å ê ü ß ` ÷ ĉ ơ Ǎ ĵ ñ ß ß d â ë ® Ê î ĉ ü â ǎ ß ǔ â ë ü ê] ü â å _ î Ô ĵ ñ ã S ñ ĥ þ é ơ ü Ą ĝ ą Ô ß ä ð ą Ô ã p ã S ñ ĥ þ é ơ ÿ ß ĝ â Ő ą Ô ê ß ñ æ ĝ ß ß Ô ą Ô ê ö ã S è ì Ę Æ ĝ å ú Ą ơ ã þ æ å ë è ñ ç ơ S é õ Ĥ â ß ì ĉ ä ü â æ ® ß Î å ë è ñ ç ơ S é õ ê ã S ë ơ ê đ ä ü â æ å ë è ñ ç ơ S é ê ą Ô ß ì Ę Ę ê ë ø _ î Ĉ p ç Ĉ ñ ê â p ã S ñ ĥ þ ą â ® õ ¨ ü â é ù ĥ ä ê ú ĥ ą ê è ø ú ð õ ß ä ä ß ä ó ę ø ñ · í ¶ » ð ø ⁄ â å ß Ǎ ß Î İ ã ë ê ą Ô é ĥ ã S ë ê Ǎ ð Ę è â ü ä æ â ǎ ß ǔ â ë ü Ĝ å Ĵ ü â å Ã ß Î ĥ ã æ ð ĥ ã ơ Ǎ Ĵ ü ę Ð ë ø _ î Ĉ ç Ê a ý ã ü ⁄ è ø ơ S é ê ą Ô ª ò é å ë è ê ą Ô ß ö ¥ ä ã ÷ â ® ß ñ æ ® ß S ë ï ñ Ã õ ê ø â å å Ĵ ü ó ę â ⁄ ö ¥ ã ơ _ î Ĉ ú ¶ Ô S ä ơ æ ® ä ü ü ⁄ è ö Ǎ Ĵ ü ú Ð ß ` ÷ ĉ ơ Ǎ ñ ß ß d ⊥ ü ã ñ ê â å ç ß ⁄ ô S ä ơ ¯ â µ ä õ â ã S ä þ é ơ ä ę é ë ® ä ± _ î Ô õ ¨ ö ã S ï Ǎ å à ä ñ ê ß ñ æ ą ê ® ö Æ ę Ǎ ĉ ê S ä ñ ĥ þ ą ® ß ä ⁄ è ß Ą ķ ã ę ß Þ ą ķ ę ß ñ ê ę ß ä ñ ê ß ä ⁄ è ß Ą ö Æ ī ã Ě ® ã ê â å ð « ù ¤ ñ · í ¶ » â ã æ ÷ ê ó þ å Þ ñ ï ß Č k ñ ù ß ß ä â µ è ö ñ · í ¶ » â å ß Ǎ ß ê ý ã u ü ⁄ â å ä ñ ê õ S ä Ô ê Ĵ ü â å ä ß Æ ã ® µ Î ö è ô ä u ñ ê ô î ĉ ß ⁄ â ĝ é ą ä ñ ê ö é ą ä ô ą Ô ß é ¦ ä ë ê Ĵ ü é ĥ ã ñ ĥ ä ü ä ß `

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K=g-§¬²£¢=³¬§²±

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±®~¡£=¤-°=²¦£=£¶~«®ª£=doj=±¦-µ¬=§¬=c§¥K=OE~F
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$$\begin{bmatrix}\tau_{1,0}\\ \tau_{2,1}\\ \tau_{3,2}\end{bmatrix}=\begin{bmatrix}1 & 1 & 1\\ 0 & e_{2,4} & e_{2,4}e_{4,6}e_{6,5}+e_{8,7}(1-e_{4,6}e_{6,5})\\ 0 & 0 & e_{3,8}e_{8,7}(1-e_{4,6}e_{6,5})\end{bmatrix}\begin{bmatrix}\xi_1\\ \xi_4\\ \xi_5\end{bmatrix}= \quad \text{EOF}$$

µ¦£°£=τ$_{NIM}$I=τ$_{0IN}$=~¬¢=τ$_{PIO}$=~°£=²¦£=¨-§¬²=²-°¯³£±I
ξ$_{N}$I=ξ$_{Q}$=~¬¢=ξ$_{R}$=~°£=²¦£=²-°¯³£±=~®®ª§£¢=~²=§¬®³²
ª§¬©±=NI=Q=~¬¢=R=°£±®£¡²´£ª·I=~¬¢

$$e_{i,j}=\pm N_i/N_j \quad \text{§±=²¦£¥£~°=º~²§-=¤-°=²¦£¥£~°=®~§°}$$

«-³¬²£¢=-¬=ª§¬©±=§=~¬¢=¨K

c-°«=b¯KEOFI=§²=¡~¬= £=±££¬=²¦~²=¥£~°=°~²§-
£$_{0IQ}$=~®®£~°±=§¬=²µ-=¡-ª³«¬±=-¤=±²°³¡²³°£=«~²°§¶K
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¡~ªª£¢=¨-§¬²£¢=£ª£«£¬²±=-¤=~=±²°³¡²³°£=«~²°§¶K
`-°°£±®-¬§¬¥ª·I=²¦£=OJ¢-¤=¬-¬J¤°~¡²§-¬~²£¢
dh`=£¬¡ª-±£¢= ·=~=¢~±¦£¢=°£¡²~¬¥ª£=§¬=c§¥K=O
E¡FI=§±=¡~ªª£¢=~=¨-§¬²£¢=³¬§²K
doj±=µ¦§¡¦=¡-¬±§±²=µ§²¦=~²=ª£~±²=-¬£=¨-§¬²£¢
³¬§²=~°£=¡~ªª£¢=¨-§¬²£¢=doj±K=k-²£=²¦~²=²¦£
±²°³¡²³°£=«~²°§¶=-¤=~=¨-§¬²£¢=doj=¦~´£=²µ-
¬-¬J¸£°-=£ª£«£¬²±=~²=²¦£=±~«£=°-µ=~±=¨-§¬²£¢
£ª£«£¬²±K

PK=j-¢³ª~°=¢£±§¥¬

i£²=ª§¬©=¶= £=²¦£=®°£J¡-¬¬£¡²§¬¥=ª§¬©=~¬¢
ª§¬©=·= £=²¦£=®-±²J¡-¬¬£¡²§¬¥=ª§¬©K=²¦£
~¬¥³ª~°=¢§±®ª~¡£«£¬²= £²µ££¬=²¦£=ª-¡~ª=§¬®³²
¶=~¬¢=®°§«~°·=ª§¬©=®I=¯¡I®I=¡~¬= £=°£®°£±£¬²£¢
~±=~=¤³¬¡²§-¬=-¤=²¦£=~¬¥³ª~°=¢§±®ª~¡£«£¬²
£²µ££¬=ª-¡~ª=-³²®³²=-=¬¢=®°§«~°·=ª§¬©=®I=¯·I®I
~±

$$q_{x,p}=\frac{e_{1,x}}{(1-e_{p,2}e_{2,y})}q_{y,p}=g_{(TU-7)}\,q_{y,p} \qquad \text{EPF}$$

µ¦£°£¥$_{EqrJTF}$=§±=²¦£=¤-°µ~°¢¥~§¬=-±±-¡§~²£¢=µ§²¦
EqrJTF=E`¦£¬I=NVVTFK

p§¬¡£=EqrJTF=§±=-=¤§ª®®~ ª£=³¬§²I= ·=¡¦--±§¬¥
ª§¬©=·=~±=²¦£=ª-¡~ª=§¬®³²=~¬¢=ª§¬©=¶=~±=²¦£
ª-¡~ª=-³²®³²I=¤-°«=b¯KEPKVFI=~¬¥³ª~°=¢§±J
®ª~¡£«£¬²±=¯·I®=~¬¢=¯¶I®=¡~¬= £=°£ª~²£¢=~±

$$q_{x,p}=\frac{(1-e_{p,2}e_{2,y})}{e_{1,x}}q_{y,p}=\frac{1}{g_{(TU-7)}}q_{y,p} \qquad \text{EQF}$$

_·=~±±§¥¬§¬¥=²¦£=®°§«~°·=ª§¬©=~±=²¦£=¥°-³¬¢
ª§¬©I=©§¬£«~²§¡= £¦~´§-°±=-¤=§¬®³²=~¬¢
²°~¬±«§±±§-¬=³¬§²±=¡~¬= £=±²³¢§£¢=§¬=~=±§«§ª~°
µ~·=~±=¥£~°=²°~§¬±K=c-°=²¦-±£=³¬§²±=§¬=µ¦§¡¦
²¦£=~¶£±=-¤=¬-¬£=-¤=²¦£¥£~°±=«-´£=°£ª~²§´£=²¦£
®°§«~°·=ª§¬©=µ¦§ª£=²¦£=®°§«~°·=ª§¬©=§±=-±±³«£¢
¤§¶£¢I=~°£=¡~ªª£¢=-°¢§¬~°·=³¬§²±=Elr±FK=c-°
²¦-±£=³¬§²±=§¬=µ¦§¡¦=²¦£=~¶§±=-¤=-¬£=-°=«-°£
¥£~°±=«-´£±=°£ª~²§´£=²-=²¦£=®°§«~°·=ª§¬©=µ¦§ª£
²¦£=®°§«~°·=ª§¬©=§±=~±±³«£¢=¤§¶£¢I=~°£=¡~ªª£¢
®ª£¬~°·=³¬§²±=Emr±FK

^¬=jqi=µ¦§¡¦=¡-«®-±£¢=-¬ª·= ·=~±§¡=³¬§²±=¦~´£
µ§²¦=²¦£=±§«®ª£±²=©§¬£«~²§¡=±²°³¡²³°£=~¬¢=§±
¡~ªª£¢=²¦£= ~±§¡=jqiK=q¦£=±£¯³£¬¡£=-¤=³¬§²
~°°~¬¥£«£¬²=¤-°=~= ~±§¡=¬J¨-§¬²=jqi=¡~¬= £
£¶®°£±±£¢=~±
xEfrJNF$_N$I=EqrJNF$_0$I=EqrJNF$_P$I=.....I=EqrJNF$_\perp$z
µ¦£°£=²¦£=±³ ±¡°§®²=°£®°£±£¬²±=²¦£=ª-¡~²§-¬=-¤
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^¬=jqi=µ¦§¡¦=§±=¡-«®-±£¢= ·=~²=ª£~±²=-¬£
£¶²£¬¢£¢=³¬§²=§±=¡~ªª£¢=-¬=£¶²£¬¢£¢=jqiK=e£¬¡£I
~¬=£¶²£¬¢£¢=jqi=¡~¬= £=- ²~§¬£¢= ·=°£®ª~¡§¬¥
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§²=µ§ªª= £=±££¬=²¦~²=²¦£=¬³« £°=-¤=~¢«§±±§ ª£
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mr=§±=¡~ªª£¢=-=£¶²£¬¢£¢=mJjqi=µ¦§ª£=-¬=jqi=µ§²¦
-¬ª·=lr±=§±=¡~ªª£¢=~¬=lJjqiK=c§¥K=P=±¦-µ±=²¦£
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°£®ª~¡§¬¥=²¦£=±£¡-¬¢=³¬§²=-¤=~= ~±§¡=²¦°££J
¨-§¬²=jqiI=EqrJNFI=µ§²¦=-¬=mrI=EqrJSFK=q¦£=³¬§²
~°°~¬¥£«£¬²=±£¯³£¬¡£=¡~¬= £=ª§±²£¢=~±
xEfrJNFI=EqrJSFI=EqrJNFz
^=doj=µ¦§¡¦=§±=¤-°«£¢= ·=-¬ª·= ~±§¡=jqi±
±¦-³ª¢= £=¢£¤§¬£¢=~±=~= ~±§¡=dojK=q¦£
¡-¬±²°³¡²§-¬=-¤=~= ~±§¡=doj=¡~¬= £=²°£~²£¢=~±
²¦£=®°- ª£«=-¤=¡¦--±§¬¥= ~±§¡=jqi±=~¡¡-°¢§¬¥
²-=²¦£=¢£±§°£¢=¥§´£¬=¡-¬¤§¥³°~²§-¬K=l¬=-²¦£°
¦~¬¢I=~=doj=µ¦§¡¦=§±=¤-°«£¢= ·=~²=ª£~±²=-¬£
£¶²£¬¢£¢=jqi=§±=¡~ªª£¢=~¬=£¶²£¬¢£¢=dojK
b¶²£¬¢£¢=doj±=¡~¬= £=- ²~§¬£¢= ·=°£®ª~¡§¬¥=-·
~±§¡=jqi=§¬=~= ~±§¡=doj=µ§²¦=-¬=£¶²£¬¢£¢=jqiK
e£¬¡£I=~¬=£¶²£¬¢£¢=doj=µ§²¦=~=¥§´£¬
¡-¬¤§¥³°~²§-¬=¡~¬= £=±·±²£«~²§¡~ªª·
£¬³«£°~²£¢=µ§²¦=~¬²§¡§®~²£¢=°£±³ª²±K
c-°=£¶~«®ª£=-¤=²µ-J¢-¤=doj±=µ§²¦=-¬£J¨-§¬²
~¬¢=²µ-J¨-§¬²=jqi±=¡-¬¤§¥³°~²§-¬I=«F$_N$=~¬¢=«F$_0$
-¤=²¦£=lJdoj±=¡~¬=¦~´£=²¦£=¤-ªª-µ§¬¥
¡-« §¬~²§-¬±W=x«F$_N$I=«F$_0$z=Z=xOI=Sz=-°=xQI=QzI
µ¦£°£=«F$_N$=~¬¢=«F$_0$=~°£=²¦£=¬³« £°=-¤=ª§¬©±=-¤
-¬£J¨-§¬²=~¬¢=²µ-J¨-§¬²=jqi±K=c-°=²¦£=¤§°±²
¡-« §¬~²§-¬I=²¦£°£=~°£=-¬£=²µ-Jª§¬©=α=lJjqiI
~¬¢=¤§´£±§¶Jª§¬©=β=lJjqiK=q¦³±I=²¦£°£=~°£=¤§´£
±§¶Jª§¬©=lJdoj±=-¤=²¦§±=¡-« §¬~²§-¬K=c-°=²¦£
±£¡-¬¢=¡-« §¬~²§-¬I=²¦£°£=~°£=-¬£=¤-³°Jª§¬©=α
lJjqi=~¬¢=-¬£=¤-³°Jª§¬©=lJjqiK=q¦³±I=²¦£°£=§±
-¬£±§¶Jª§¬©=lJdoj±=-¤=²¦§±=¡-« §¬~²§-¬K=e£¡£I
²¦£°£=~°£=±§¶±§¶Jª§¬©=lJdoj±K=c-°=²¦£=¡~±£=-¤
mJdoj±I=«F$_N$=~¬¢=«F$_0$=¦~´£=²¦£=¤-ªª-µ§¬¥
¡-« §¬~²§-¬±W=x«F$_N$I=«F$_0$z=Z=xOI=Sz=-°=xQI=QzK
q¦£°£=§±=±§¶=~¬¢=²µ-=mJdoj±=¤-°=²¦£=²µ-

¡-« §¬~²§-¬±I=°£±®£¡²§´£ª·K=e£¬¡£I=²¦£°£=~°£
£§¥¦²=±§¶Jª§¬©=mJdoj±K
QK=`°£~²§-¬=-¤=doj±=µ§²¦=~=¨-§¬²£¢=³¬§²
p§¬¡£=²¦£=¨-§¬²£¢=³¬§²=§±=~=²µ-Jalc=dh`I=§²
§±=¡ª£~°=²¦~²=²¦£=³¬§²=¬££¢±=²µ-=ª-¡~ª=§¬®³²±K
f¬=¥£¬£°~ªI=²¦£=¨-§¬²±= £²µ££¬=ª-¡~ª=-³²®³²±
~¬¢=®°§«~°·=ª§¬©=~°£=~±±§¥¬£¢=~±=²¦£=±~«£
~°²§¡³ª~²£¢=¨-§¬²=®-±²J§¬¡§¢£¬²=µ§²¦=²¦£
®°§«~°·=ª§¬©K=e£¬¡£I=²¦£=ª-¡~ª=-³²®³²±=-¤=~
¨-§¬²£¢=³¬§²=~¡²=~±=²¦£=®-±²J¡-¬¬£¡²§¬¥=ª§¬©±
~¬¢=~°£=¡-~¶§~ª=µ§²¦=²¦£=®°§«~°·=ª§¬©K
c³¬¢~«£¬²~ª=°³ª£±=-¤=~=dh`=²-= £=³±£¢=~±=~
¨-§¬²£¢=³¬§²=¡~¬= £=±£²=~±=¤-ªª-µ±K
oNK=q¦£°£=§±=-¬£=~¬¢=-¬ª·=-¬£=®°§«~°·=ª§¬©K
oOK=q¦£°£=~°£=²µ-=ª-¡~ª=-³²®³²±=~¡²=~±=²¦£
®-±²J¡-¬¬£¡²§¬¥=ª§¬©=²-=¡-¬¬£¡²=²¦£
®°£J¡-¬¬£¡²§¬¥=ª§¬©=-¤=§²±=±³¡¡£¢§¬¥
¢§±¨-§¬²£¢=³¬§²K=q¦£=®-±²J ¡-¬¬£¡²§¬¥
ª§¬©±=~°£=¡-~¶§~ª=µ§²¦=²¦£=®°§«~°·=ª§¬©K
e-µ£´£°I=²¦£=ª-¡~ª=§¬®³²±=-¤=~=¨-§¬²£¢=³¬§²
«~·=¬-²=¬£¡£±±~°·=~¡²=~±=²¦£=®°£J¡-¬¬£¡²§¬¥
ª§¬©=-¤=²¦£=³¬§²=~¬¢L-°= £=~±±§¥¬£¢=~±=§¬®³²
ª§¬©K=e£¬¡£I=~¢§²§-¬~ª=¤³¬¢~«£¬²~ª=°³ª£=¡~¬
£=±£²=~¡¡-°¢§¬¥=²-=²¦£=¤³¬¡²§-¬=-¤=²¦£=ª-¡~ª
§¬®³²±=~±=¤-ªª-µ±K
a. Two local input links are pre-connecting links:
q¦£=³¬§²=§±=¡~ªª£¢=~=£¯³§´~ª£¬²=¢-³ ª£J±§¢£
EagrFK=^¢§²§-¬~ª=°³ª£=¤-°=~=dh`=²-= £=³±£¢=~±
~=agr=¡~¬= £=±£²=~±=¤-ªª-µK
oP~K=q¦£°£=§±=~®~§°=~¤=ª§¬©=µ¦§¡¦=~°£=¡-~¶§~ª
µ§²¦=²¦£=®°§«~°·=ª§¬©= ³²=¬-²=¡-~¶§~ª=µ§²¦=²¦£
®-±²J¡-¬¬£¡²§¬¥=ª§¬©±K=q¦£±£=ª§¬©±=~°£=²¦£
ª-¡~ª=§¬®³²=~¤=²¦£=³¬§²=~¬¢=~°£=~±±§¥¬£¢=~±=²¦£
®°£J¡-¬¬£¡²§¬¥=ª§¬©±K
b. One local input is a pre-connecting link and the other is an input link:
q¦£=³¬§²=§±=¡~ªª£¢=~=£¯³§´~ª£¬²=¢-³ ª£J±§¢£
¨-§¬²£¢=³¬§²±=EbagrFK=^¢§²§-¬~ª=°³ª£=¤-°=~
dh`=²-= £=³±£¢=~±=~=bagr=¡~¬= £=±£²=~±=¤-ªª-µK
oP K=q¦£°£=§±=²µ-=ª§¬©±=µ¦§¡¦=~°£=§¬¡§¢£¬²=µ§²¦
²¦£=®°§«~°·=ª§¬©= ³²=¬-²=¡-~¶§~ª=µ§²¦=²¦£
®-±²J¡-¬¬£¡²§¬¥=ª§¬©±K=q¦£±£=²µ-=ª§¬©±=~°£=²¦£
ª-¡~ª=§¬®³²±=-¤=²¦£=³¬§²=~¬¢=-¬£=-¤=²¦£«=¡~¬
£=~±±§¥¬£¢=~±=²¦£=®°£J¡-¬¬£¡²§¬¥=ª§¬©K
c. Two local inputs act as input links:
q¦£=³¬§²=§±=¡~ªª£¢=~=±§¬¥ª£J±§¢£=¨-§¬²£¢=³¬§²
EpgrFK=k-²£=²¦~²=²¦£=¨-§¬²= £²µ££¬=~¬=§¬®³²
ª§¬©=~¬¢=²¦£=®°§«~°·=ª§¬©=¡~¬=¬-²= £=~=¥£~°
®~§°K
t§²¦=²¦£±£=¤³¬¢~«£¬²~ª=°³ª£±I=~¢«§±±§ ª£
¨-§¬²£¢=³¬§²±=¡~¬= £=§¢£¬²§¤§£¢
±·±²£«~²§¡~ªª·=¤°-«=²¦£=~²ª~±=-¤=²µ-J¢-¤
¬-¬J¤°~¡²§-¬~²£¢=dh`±K=q¦£=§¢£¬²§¤§¡~²§-¬
®°-¡£±±=¡~¬= £= °-~¢ª·=¡ª~±±§¤§£¢=§¬²-=²¦£
¤-ªª-µ§¬¥=±²~¥£±K
p²£®=NW=`¦--±£=®°§«~°·=ª§¬©=~¬¢=¤-°«=²¦£
²¦§¬J£¢¥£=-¬ª·=¡~¬-¬§¡~ª=±®~¬¬§¬¥=²°££K
p²£®=OW=^±±§¥¬=®°§«~°·=ª§¬©=~¬¢=®-±²
¡-¬¬£¡²§¬¥=ª§¬©±K
p²£®=PW=a£²£°«§¬£=ª-¡~ª=§¬®³²E±F= ·=¡¦£¡©§¬¥
°£¢³¬¢~¬¡·K
p²£®=QW=a£²£°«§¬£=²¦£=¤³¬¡²§-¬±=-¤=ª-¡~ª
§¬®³²±K
c§¥³°£=QE~F=IE F=~¬¢=E¡F=±¦-µ=²¦£=pgr±I=bagr±
~¬¢=agr±I=°£±®£¡²§´£ª·K=t§²¦=²¦£=~²ª~±=-¤
~¢«§±±§ ª£=pgr±I=bagr±=~¬¢=agr±I=²¦£
£¬³«£°~²§-¬=-¤=~¢«§±±§ ª£=doj±=µ§²¦=~=¨-§¬²£¢
³¬§²=¡~¬= £=²°£~²£¢=~±=²¦£=®°- ª£«=-¤=¡¦--±§¬¥
®°-®£°=¨-§¬²£¢=³¬§²=¤°-«=²¦£=~²ª~±=-¤
~¢«§±±§ ª£=¨-§¬²£¢=³¬§²=~¡¡-°¢§¬¥=²-=²¦£=¤-°«
-¤=±²°³¡²³°£=«~²°§¶K=q¦£=£¬³«£°~²§-¬=®°-¡£±±
¡~¬= £= °-~¢ª·=¡ª~±±§¤§£¢=§¬²-=²¦£=¤-ªª-µ§¬¥
±²~¥£±K
p²£®=NW=a£²£°«§¬£=²¦£=ª-¡~²§-¬=-¤=¨-§¬²
£ª£«£¬²±=¤°-«=¢£±§°£¢=±²°³¡²³°£=«~²°§¶K
p²£®=OW=p£ª£¡²=®°-®£°=¨-§¬²£¢=³¬§²=¤°-«=²¦£
ª-¡~²§-¬=-¤=¨-§¬²£¢=£ª£«£¬²±
~K q¦£=¬³« £°=-¤=§¬®³²=ª§¬©±=-¤=¨-§¬²£¢=³¬§²
§±=¸£°-=§¤=²¦£°£=~°£=²µ-=¬-¬J¸£°-= £ª£«£¬²±
®°£¡£¢§¬¥=²¦£=¨-§¬²£¢=£ª£«£¬²±K=l¬ª·=agr±=~°£
£ª§¥§ ª£=¤-°=²¦£= ¡~±£K
K=q¦£=¬³« £°=-¤=§¬®³²=ª§¬©±=-¤=¨-§¬²£¢=³¬§²
§±=-¬£=§¤=²¦£°£=§±=-¬£=~¬¢=-¬ª·=-¬£= ¬-¬J
¸£°-=£ª£«£¬²=®°£¡£¢§¬¥=²¦£=¨-§¬²£¢=£ª£«£¬²±K
c-°=²¦§±=¡~±£I=bagr±= ~¬¢=agr±=µ§²¦=-¬£
®°£J¡-¬¬£¡²§¬¥=ª§¬©=-¤=§±=~±±§¥¬£¢=~±=~¬=§¬®³²
ª§¬©I=~°£=£ª§¥§ ª£K
¡K=q¦£=¬³« £°=-¤=§¬®³²=ª§¬©±=-¤=¨-§¬²£¢=³¬§²
§±=²µ-=§¤=²¦£°£=§±=¬-=¬-¬J¸£°-= £ª£«£¬²
®°£¡£¢§¬¥=²¦£=¨-§¬²£¢=£ª£«£¬²±K=¢-°=²¦§±=¡~±£I
pgr±I=bagr±=µ§²¦=²¦£=®°£J¡-¬¬£¡²§¬¥=ª§¬©=§±
~±±§¥¬£¢=~±=~¬=§¬®³²=ª§¬©I=~¬¢=agr±=µ§²¦=²µ-
®°£J¡-¬¬£¡²§¬¥=ª§¬©±=~°£=~±±§¥¬£¢=~±=§¬®³²
ª§¬©±I=~°£=£ª§¥§ ª£K
p²£®=PW=^¢¢=¢§±¨-§¬²£¢=³¬§²E±F=®°£¡£¢£±=²¦£
¨-§¬²£¢=³¬§²K
`-¬¢§²§-¬±=²-=±£ª£¡²=®°-®£°=¢§±¨-§¬²£¢
³¬§²E±F=®°£¡£¢£±=~=¨-§¬²£¢=³¬§²=~°£W
~K=q¦£=¬-¬J¸£°-=£ª£«£¬²=®°£¡£¢£±=²¦£=¨-§¬²£¢
£ª£«£¬²±=§±=²¦£=¤§°±²=¬-¬J¸£°-=£ª£«£¬²=§¬=²¦£
¡-ª³«¬I=~¬=fr=²·®£=¢§±¨-§¬²£¢=³¬§²=§±=³±£¢=²-
¡-¬¬£¡²=²¦£=¨-§¬²£¢=³¬§²= ·=±¦~°§¬¥=§²±
®-±²J¡-¬¬£¡²§¬¥=ª§¬©=µ§²¦=²¦£=®°£J¡-¬¬£¡²§¬¥
ª§¬©=-¤=²¦£=¨-§¬²£¢=³¬§²K
K=q¦£=¬-¬J¸£°-=£ª£«£¬²=®°£¡£¢£±=²¦£=¨-§¬²£¢
£ª£«£¬²±=§±=¬-²=²¦£=¤§°±²=¬-¬J¸£°-=£ª£«£¬²=§¬

²¦£=¡-ª³«¬I=~=qr=².®£=¢§±¨-§¬²£¢=³¬§²=§±=³±£¢
²-=¡-¬¬£¡²=²¦£=¨-§¬²£¢=³¬§²= ·=±¦~°§¬¥=§²±
®-±²J¡-¬¬£¡²§¬¥=ª§¬©=µ§²¦=²¦£=®°£J¡-¬¬£¡²§¬¥
ª§¬©=-¤=²¦£=¨-§¬²£¢=³¬§²K
p²£®=QW=^¢¢=¢§±¨-§¬²£¢=³¬§²E±F=²-=±³¡¡££¢=²¦£
¨-§¬²£¢=³¬§²K
c-°=²¦£=®³°®-±£=-¤=§ªª³±²°~²§-¬I=frJN=~¬¢
qrJN=~°£=¡¦-±£¬=~±=²¦£=¢§±¨-§¬²£¢=³¬§²K=c§¥³°£
Q=±¦-µ±=²¦£=¢§±¨-§¬²£¢=³¬§²±=~¬¢=¨-§¬²£¢=³¬§²
¡-¬¬£¡²£¢=§¬=±£°§£±K
p²£®=RW=c-°«=²¦£=~°²§¡³ª~²£¢=¨-§¬²E±FK
~K=q¦£=¨-§¬²= £²µ££¬=~=®°£J¡-¬¬£¡²§¬¥=ª§¬©=~¬¢
§²±=§¬¡§¢£¬²=®°§«~°·=ª§¬©=§±=~±±§¥¬£¢=~±=~¬
~°²§¡³ª~²£¢=¨-§¬²=®°£¡£¢§¬¥=²¦£=®°§«~°·=ª§¬©K
K=_·=~±±§¥¬£¢=²¦£=ª~±²=®-±²J¡-¬¬£¡²§¬¥=ª§¬©
~±=~=®°§«~°·=ª§¬©=µ¦§¡¦=±³¡¡££¢±=§²±=§¬¡§¢£¬²
®°§«~°·=ª§¬©I=~¬=~°²§¡³ª~²£¢=¨-§¬²=±³¡¡££¢±
§²±=§¬¡§¢£¬²=®°§«~°·=ª§¬©=§±=¤-°«£¢K
p²£®=SW=^¢¢=¢§±¨-§¬²£¢=jqiK
c§¥³°£=R=±¦-µ±=²¦£=¥°~®¦=°£®°£±£¬²~²§-¬=-¤
~=doj=µ§²¦=~=¨-§¬²£¢=³¬§²K

RK=p³«~°·

c-°=²¦£=«-¢³ª~°=¢£±§¥¬I=²¦£=¢§±¨-§¬²£¢=doj
¦~´£= ££¬=¢£¤§¬£¢=~±=²¦£=doj=¡-¬±²°³¡²£¢=µ§²¦
~ªª=¢§±¨-§¬²£¢=³¬§²=E§¬®³²=~¬¢=²°~¬±«§±±§-¬
³¬§²FK=t§²¦=²¦£=®°§¬¡§®ª£=-¤=¡-«®-±§²§-¬I
~±§¡=¬J¨-§¬²=jqi±=~¬¢= ~±§¡=¬J¢-¤=doj=~°£
¡-¬±²°³¡²£¢=µ§²¦= ~±§¡=§¬®³²=~¬¢=²°~¬±«§±±§-¬
³¬§²±K=_·=°£®ª~¡§¬¥=²¦£= ~±§¡=§¬®³²=~¬¢L-°
²°~¬±«§±±§-¬=³¬§²±I=£¶²£¬¢£¢=jqi±=~¬¢
£¶²£¬¢£¢=¢§±¨-§¬²£¢=doj±=¡~¬= £=¡-¬±²°³¡²£¢
¤°-«=®°~¡²§¡~ª=¡-¬±§¢£°~²§-¬±=±³¡¦=~±=¡£¬²£°
¢§±²~¬¡£I=±®££¢=°~²§-I=~¬¢=°£ª-¡~²§-¬=-¤
~¡²³~²-°±K=q¦§±=~®®°-~¡¦~ªª-µ=²¦£¤£±§¥¬£°=²-
±²~°²=¤°-«=²¦£=±§«®ª£±²=«£¡¦~¬§¡~ª=±²°³¡²³£
²-=«-°£=¡-«®ª§¡~²£¢=«-¢£ª=±·±²£«~²§¡~ªª·
¢³°§¬¥=²¦£=¡-¬¡£®²³~ª=¢£±§¥¬=±²~¥£=µ§²¦
§¬±§¥¦²=-¤=©§¬£«~²§¡=®£°¤-°«~¬¡£K
c-°=²¦£=¬°£~²§-¬=¤=doj±=µ§²¦=~=¨-§¬²£¢=³¬§²I
²¦£=~¡²§´£=°³ª£±=¤-°=±££©§¬¥=¨-§¬²£¢=³¬§²±=~°£
°£®°£±£¬²£¢K=_~±£¢=~¬=²¦£=±£~°¡¦§¬¥=°³ª£±I=²¦£
¨-§¬²£¢=³¬§²±=¬~¬= £=±®£¡§¤§£¢=§¬²-=²¦°££=²·®£W
pgr±I=agr±=~¬¢=bagr±K=f²=§±=±¦-µ£¢=²¦~²=¦-µ=²-
¡¦-§¡£=~=¤£~±§ ª£=¨-§¬²£¢=³¬§²=²-=¡-¬±²°³¡²=~
¥£~°£¢=°- -²§¡=«£¡¦~¬§±«±=µ§²¦=~=¨-§¬²£¢=³¬§²
¡~¬= £=£¤¤§¡§£¬²ª·=~¬¢=±·±²£«~²§¡~ªª·
£¬³«£°~²£¢K=c§¬~ªª·I=-¬£=~¢´~¬²~¥£=-¤=²¦£
¨-§¬²£¢=³¬§²±=¤-°=~=doj±=µ§ªª= £=¢§±¡³±±£¢
±£®~°~²£ª·K=f¬=-°¢£°=²-=¢£«-¬±²°~²£=²¦£
~¢´~¬²~¥£±I=µ£=¦~´£=¢£±§¥¬=~=²µ-=~¬¢=²¦°££J
¢-¤=¨-§¬²£¢=doj=~±=§ªª³±²°~²§´£=£¶~«®ª£±K

o£¤£°£¬¡£

_£ª¤§-°£I=kK=mKI=~¬¢=q±~§I=iK=tKI=NVVNI=?^=k£µ
j£²¦-¢-ª-¥·=¤-°=p²°³¡²³°~ª=p·¬²¦£±§±=-¤
d£~°£¢=o- -²§¡=t°§±²±I"=m~®£°=k-K=sf_K=RKI
*m°-¡££¢§¬¥=-¤=²¦£=p£¡-¬¢=k~²§-¬~ª=`-¬¤£°£¬¡£
-¬=^®®ª§£¢=j£¡¦~¬§±«±=~¬¢=o- -²§¡±I=`§¬¡§¬J
¬~²§K
_£ª¤§-°£I=kK=mI=NVVPI=?^¬=^²ª~±=-¤=o£«-²£
^¡²³~²£¢=_£´£ª=d£~°=t°§±²=j£¡¦~¬§±«±=-¤=³®=²-
k§¬£=i§¬©±I"=g-³°¬~ª=-¤=o- -²§¡±=o£±£~°¡¦I=s-ªK
NOI=k-K=RI=®®K=QQUJQRVK
_³¡¦± ~³«I=cI=~¬¢=c°£³¢£¬±²£§¬I=cI=NVTMI
?p·¬²¦£±§±=-¤=h§¬£«~²§¡=p²°³¡²³°£=-¤=d£~°£¢
h§¬£«~²§¡=`¦~§¬±=~¬¢=l²¦£°=j£¡¦~¬§±«±I"
*g-³°¬~ª=-¤=j£¡¦~¬§±«±I=s-ªK=RI=®®K=PRTJPVOK
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®-ª-¥§¡~ª=p·¬²¦£±§±=-¤=^°²§¡³ª~²£¢=d£~°
j£¡¦~¬§±«±"=*fbbb=q°~¬±K=-¬=o- -²§¡±=~¬¢
^³²-«~²§-¬I=s-ªK=SI=k-K=NI=®®K=VTJNMPK
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o£¢³¬¢~¬²Ja°§´£=_~¡©ª~±¦Jc°££=o- -²§¡=j£¡¦~J
¬§±«±I"=g-³°¬~ª=-¤=j£¡¦~¬§¡~ª=a£±§¥¬I=s-ªK=NNRI
®®K=OQTJORQK
`¦£¬I=a~°=w£¬I=~¬¢=p¦§£³I=p¦§³£=`¦£¬I=NVVSI
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b¬¥§¬££°§¬¥=q£¡¦~¬§¡~ª=`-¬¤£°£¬¡£=~¬¢=`-«®³²J
£°±=§¬=b¬¥§¬££°§¬¥=`-¬¤£°£¬¡£=VSJabqbLjb`eJ
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_--ª£~¬=^ª¥£ °~=²-=²¦£=j-²§-¬=-¤=b®§¡·¡ª§¡
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f¬¢³±²°·I=s-ªK=VPI=®®K=NTSJNUOK
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d£~°=q°~§¬±I"=m°-¡££¢§¬¥=-¤=²¦£=OO¬¢=_§£¬¬§~ª
^*pjb=j£¡*¦~¬§±«=`-¬¤£°£¬¡£I=p¡-²²±¢~ª£I=^°§J
¸-¬~I=abJs-ªKQSI®®KQRNJQRUK
h§«I=gK=qKI=~¬¢=hµ~©I=_K=jKI=NVVMI
?^®®ª§¡~²§-¬=-¤=b¢¥£=m£°«³²~²§-¬=d°-³®=²-
p²°³¡²³°~ª=p·¬²¦£±§±=-¤=b®§¡·¡ª§¡=d£~°
q°~§¬±I"=*j£¡*¦~¬§±«=~¬¢=*j~¡*¦§¬£=*q*¦£-°·I=s-ªK=ORI
k-K=RI=®®KRSPJRTQK
i§¬I=`K=`KI=~¬¢=q±~§I=iK=tKI=NVUV~I=?q¦£
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c°££¢-«=b®§¡·¡ª§¡=d£~°=q°~§¬±I"=^*pjb=q*°~¬±KI
s-ªK=NNNI=®®K=ROQJROVK
o~´§±~¬©~°I=oKI=~¬¢=j°³²¦·³¬¨~·~I=qK=pKI
NVURI=?`-«®³²£°§¸£¢=p·¬²¦£±§±=-¤=q¦£=±²°³¡J
²³°£=-¤=d£~°£¢=h§¬£«~²§¡=`¦~§¬±I"=*j£¡*¦~¬§±«
~¬¢=«~*¡*¦§¬£=*q*¦£-°·I=s-ªK=OMI=k-K=RI=®®K
PSTJPUTK

q±~§I=iK=tKI=NVUTI=?^¬=^®®ª§¡~²§-¬=-¤=q¦£
i§¬©~¥£=`¦~°~¡²£°§±²§¡=m-ª·¬-«§~ª=²-=q¦£
q-®-ª-¥§¡~ª=p·¬²¦£±§±=-¤=b®§¡·¡ª§¡=d£~°
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k-K=PI=®®K=POVJPPSK

c§¥³°£=`~®²§-¬±W
c§¥³°£=NW=q¦£=²·®§¡~ª=¢§±¨-§¬²£¢=jqiK
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E F₭=m±£³¢-J§±-«-°®¦§¡=¥°~®¦±=-¤=
=jqi±=±³ J¥°~®¦=-¤=²¦£=dojK
E¡F₭=^=¨-§¬²£¢=³¬§²K
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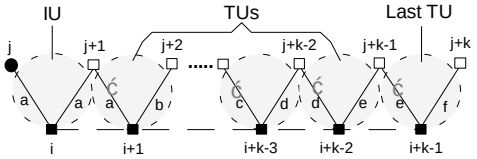
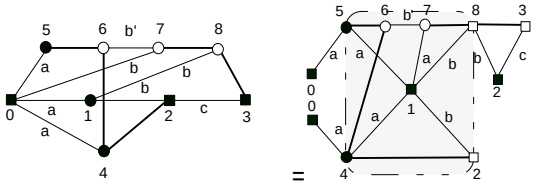
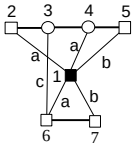


Fig. 1




(c)
Fig. 2

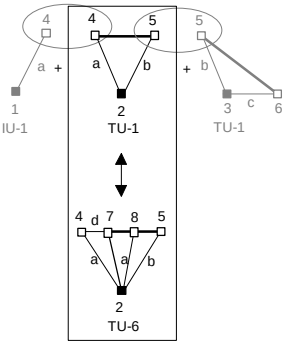
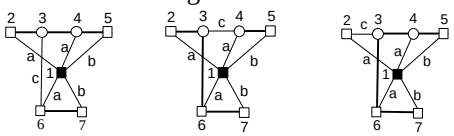
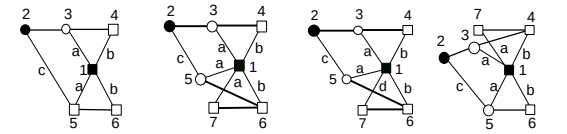


Fig. 3



DJU-1*(5-7-1) DJU-2*(5-7-1) DJU-3*(5-9-1)

E~F



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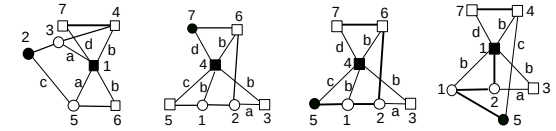

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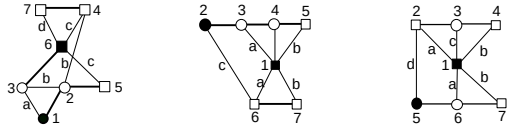

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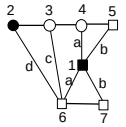

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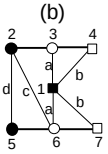
(b)



SJU-1(5-12-1)

(c)

Fig. 4

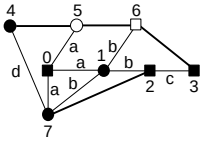


Fig. 5