Calculations

③ (1) $\lambda_s = h_s = 140$ mm

$$\min(\theta_s) = \arcsin\left(\frac{h_E}{\lambda_s}\right)$$

$$= \arcsin\left(\frac{90}{140}\right)$$

$$= 40.01°$$

(2) $\lambda_E = R_0 - \lambda_s \cos(\min(\theta_s))$

$$= 220 - 140 \cos(40°)$$

$$= 112.75 \text{ mm}$$

$$\max(\theta_E) = \arcsin\left(\frac{h_{WR}}{\lambda_E}\right)$$

$$= \arcsin\left(\frac{65}{112.75}\right)$$

$$= 35.20°$$

(5) $R_i = \lambda_E \cos(\max(\theta_E)) = 92.13$ mm

(7) $\lambda_w = 85$ mm

$$L \simeq 2\lambda_w + \frac{\pi}{2}(d_2 + d_1) + \frac{(d_2 - d_1)^2}{4\lambda_w}$$

$$\simeq 2(85) + \frac{\pi}{2}(46.57 + 15.52) + \frac{(46.57 - 15.52)^2}{4(85)}$$

$$\simeq 270.37 \text{ mm}$$

choose $L = 268.22$ mm

(8) $X = L - \pi \dfrac{(d_2 + d_1)}{2} = 268.22 - \pi\dfrac{(46.57 + 15.52)}{2} = 170.69$ mm

$$\lambda_w = \frac{X + \sqrt{x^2 - 2(d_2 - d_1)^2}}{4} = 83.91 \text{ mm}$$

(10) $L \simeq 2l_s + \frac{\pi}{2}(d_2 + d_1) + \frac{(d_2 - d_1)^2}{4l_s}$

$\simeq 2(140) + \frac{\pi}{2} \cdot 2(19.40) + 0$

$\simeq 340.95 \text{ mm}$

choose $L = 335.28 \text{ mm}$

(11) $X = L - \pi \frac{(d_2 + d_1)}{2} = 335.28 - \pi \frac{2 \cdot (19.40)}{2} = 274.33 \text{ mm}$

$l_s = \frac{X + \sqrt{X^2 - 2(d_2 - d_1)^2}}{4} = 137.17 \text{ mm}$

(15) $L \simeq 2l_E + \frac{\pi}{2}(d_2 + d_1) + \frac{(d_2 - d_1)^2}{4l_E}$

$\simeq 2(112.75) + \frac{\pi}{2} \cdot 2(19.4) + 0$

$\simeq 286.45 \text{ mm}$

choose $L = 284.48 \text{ mm}$

(16) $X = L - \pi \frac{(d_2 + d_1)}{2} = 284.48 - \pi \frac{2 \cdot (19.40)}{2} = 223.53 \text{ mm}$

$l_E = \frac{X + \sqrt{X^2 - 2(d_2 - d_1)^2}}{4} = 111.77 \text{ mm}$

① → **torque**

$$\theta_{max} = max(\pi - (\theta_E + \theta_S)) = max(180° - (0° + 40°))$$
$$= 140°.$$

$$l_o = \sqrt{l_S^2 + l_E^2 - 2l_S l_E \cos\theta_{max}}$$
$$= \sqrt{(137.17)^2 + (111.77)^2 - 2(137.17)(111.77)^2 \cos 140°}$$
$$= 234.09 \text{ mm} = 0.23 \text{ m}$$

$$M_o = A(l_S + l_E)\rho$$
$$= (0.99 \times 10^{-3})(137.17 + 111.77)(2.7 \times 10^3)$$
$$= 665.42 \text{ g} = 0.67 \text{ kg}$$

$$T_S = \eta l_o^2 (M + \frac{M_o}{3})$$
$$= (2\pi)(0.23)^2 (0.3 + \frac{0.67}{3})$$
$$= 0.17 \text{ Nm}$$

since $R_o = 220 \text{ mm} \leq l_o = 234.09 \text{ mm}$,

$$T_g = g l_o (M + \frac{M_o}{2})$$
$$= (9.81)(0.23)(0.3 + \frac{0.67}{2})$$
$$= 1.43 \text{ Nm}$$

•) $T_a > \dfrac{T}{i_S} = \dfrac{0.17 + 1.43}{3} = 0.53 \text{ Nm}$

•) $i_G T_M > \dfrac{T}{i_S} \rightarrow i_G > \dfrac{0.53}{0.16} = 3.3$

→ **positioning error**

•) **radial**

choose $T_a = 0.56 \text{ Nm}, \ i_G = 10$

$$\Delta\theta \leq \frac{0.2 \ i_G \ i_S \ i_E}{l_S i_E max(\sin\theta_S) + l_E i_S max(\sin\theta_E)} \cdot \frac{180°}{\pi}$$
$$= 1.7° \ \times$$

choose $T_a = 0.8$ Nm, $i_G = 18$

$$\Delta\theta \leq \frac{0.2 \; i_G \; i_s \; i_E}{\lambda_s i_E \max (\sin\theta_s) + \lambda_E i_s \max (\sin\theta_E)} \cdot \frac{180°}{\pi}$$

$$= 3.1° \checkmark$$

•> height

$$\Delta\theta \leq \frac{0.2 \; i_G \; i_s \; i_E}{\lambda_s i_E \max (\cos\theta_s) + \lambda_E i_s \max (\cos\theta_E)} \cdot \frac{180°}{\pi}$$

$$= 2.9° \checkmark$$

•> tangential

$$\Delta\theta \leq \frac{0.2 \; i_w \; i_G}{\lambda_E \max (\cos\theta_E) + \lambda_s \max (\cos\theta_s)} \cdot \frac{180°}{\pi}$$

$$= 2.9° \checkmark$$

## Summary

$R_0 \simeq 220 \, mm$, $h_E \simeq 90 \, mm$, $h_{WR} = 65 \, mm$, $h_S = 140 \, mm$

① Stepper motor ⟵ from appendix 17

(1) $\Delta\theta = 1.8°$

(2) $T_a = 0.56 \, Nm$

(3) $f_0 = i_w i_G \omega / \Delta\theta$

$= (3)(10) \left(\frac{\pi}{12} \cdot \frac{180°}{\pi}\right) \cdot \left(\frac{1}{1.8°}\right)$

$= 250 \, Hz$

(4) $t_0 = 1000\Delta\theta / (i_w i_G \eta) = 0.093 \, s$

(5) $\omega_{WR} = (f_0 \Delta\theta / i_{WR} i_G)$

$= (250) \left(1.8 \cdot \frac{\pi}{180}\right) \cdot \left(\frac{1}{2}\right) \cdot \left(\frac{1}{18}\right)$

$= \frac{5\pi}{72} \, \frac{rad}{s}$

$(2\pi \cdot \frac{180°}{\pi})$ (6) $\omega_H = (z_5 / z_6) \omega_{WR} = \frac{5\pi}{36} \, \frac{rad}{s}$

$\underset{40}{\downarrow} \quad \underset{20}{\downarrow}$

Model number of selected stepper motor (reduction ratio $i_G$):

CSK 243 AP-SG18     $(i_G = 18)$ ⟵ from appendix 17

② End effector ⟵ from appendix 19

(7) Air gripper: Operation range   24.9 ~ 30.9 mm

Air pressure   0.5 MPa

Maximum grasping force   27 N

weight   0.115 kg

Model number of selected endeffector:

MHZ2 - 16S ⟵ from appendix 19

③ Design Parameters

a. Operation range of each joint

(1) $40° \leq \theta_S \leq 90°$ ←

(2) $0° \leq \theta_E \leq 35°$ ←

(3) $-90° \leq \theta_W \leq 90°$

(4) $-30° \leq \theta_{WR} \leq 30°$

(5) $R_i = 92.13\ mm$ ←

from requirement

b. Timing pulley and timing belt for waist joint $(i_W = 3)$

(6) $z_1 = 24$, $d_1 = 15.52\ mm$, $z_2 = 72$, $d_2 = 46.57\ mm$

   Model number: $\begin{cases} z_1 : ATP24MXL025 ← \\ z_2 : ATP72MXL025 ← \end{cases}$

(7) $L = 268.22\ mm$, $b = 6.4\ mm$ (#.of tooth: 132) ←

   Model number: TBN132MXL025

(8) $l_W = 83.91\ mm$ ←

from appendix 15

c. Timing pulley, timing belt and gear for shoulder joint and elbow joint. $(i_S = i_E = 3)$

(9) $m = 0.8\ mm$, $\alpha = 20°$, $z_1 = 30$, $z_2 = 90$, $b = 5\ mm$

   Model number: $\begin{cases} z_1 : S80SU30B+0505 ← \\ z_2 : S80SU90B+0508 ← \end{cases}$

from appendix 12 (spur)

(10) $L = 335.28\ mm$ (# of tooth : 165) ←

   Model number: TBN165MXL025

(11) $l_S = 137.17\ mm$ ←

from appendix 15

d. Timing pulley, timing belt and gear for <u>hand</u> and
   <u>wrist</u> joint ($i_{WR} = 2$)

   (12) $m = 0.5\,mm$, $\alpha = 20°$, $z_1 = 40$, $z_2 = 80$,

   $b_1 = 5\,mm$, $b_2 = 2\,mm$

   Model number: $\begin{cases} z_1 : S50S40B+0505 \\ z_2 : S50B80A-0208 \end{cases}$ ← from appendix 13 (spur)

   (13) $m = 0.8\,mm$, $\alpha = 20°$, $z_1 = 20$, $z_2 = 40$

   Model number: $\begin{cases} z_1 : B80B20 \\ z_2 : B80B40 \end{cases}$ ← from appendix 12 (bevel)

   (14) $z_1 = z_2 = 30$, $d_1 = d_2 = 19.4\,mm$

   Model number: ATP 30 MXL 025 ←

   (15) $L = 284.48\,mm$ (# of tooth: 140.) ← from appendix

   Model number: TBN140 MXL 025 ← 15

   (16) $\lambda_E = 111.77\,mm$ ←