Derivation of the Normal Form for a Three-Alternative Decision Model (Based on Roxin, 2019)

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1 Model and Expansion

We consider the following system for three alternatives:

$$\tau\,\dot{r}_L = -r_L + \phi\Big(s_L\,r_L - c\,r_I + I_L + U\Big) + \xi_L(t), \tag{1}$$

$$\tau\,\dot{r}_C = -r_C + \phi\Big(s_C\,r_C - c\,r_I + I_C + U\Big) + \xi_C(t), \tag{2}$$

$$\tau\,\dot{r}_R = -r_R + \phi\Big(s_R\,r_R - c\,r_I + I_R + U\Big) + \xi_R(t), \tag{3}$$

$$\tau_I\,\dot{r}_I = -r_I + \phi_I\Big(\frac{g}{3}(r_L + r_R + r_C) + I_I\Big) + \xi_I(t). \tag{4}$$

In a summarized form:

$$\tau\,\dot{r}_i = -r_i + \phi\Big(s_i\,r_i - c\,r_I + I_i + U\Big) + \xi_i(t), \quad i = L, C, R, \tag{5}$$

$$\tau_I\,\dot{r}_I = -r_I + \phi_I\Big(\frac{g}{3}(R_L + R_C + R_R) + I_I\Big) + \xi_I(t), \tag{6}$$

where:

- r_i is the firing rate of excitatory population i.
- r_I is the firing rate of the inhibitory population.
- s_i is the self-excitation coefficient (which may differ among populations).
- c is the inhibition coefficient.
- I_i are each population external input.
- U is a ramping urgency signal. We assume it varies slowly:

  $$U = U_0 + \varepsilon^2\,\Delta U.$$

  As U is a ramping signal, we have that $U_0 = 0$
- τ and τ_I are the time constants for the excitatory and inhibitory populations, respectively.

Our goal is to derive a reduced (normal form) model that captures the critical dynamics in a two-dimensional competitive subspace.

An schematic representation of the model is shown in figure 1.

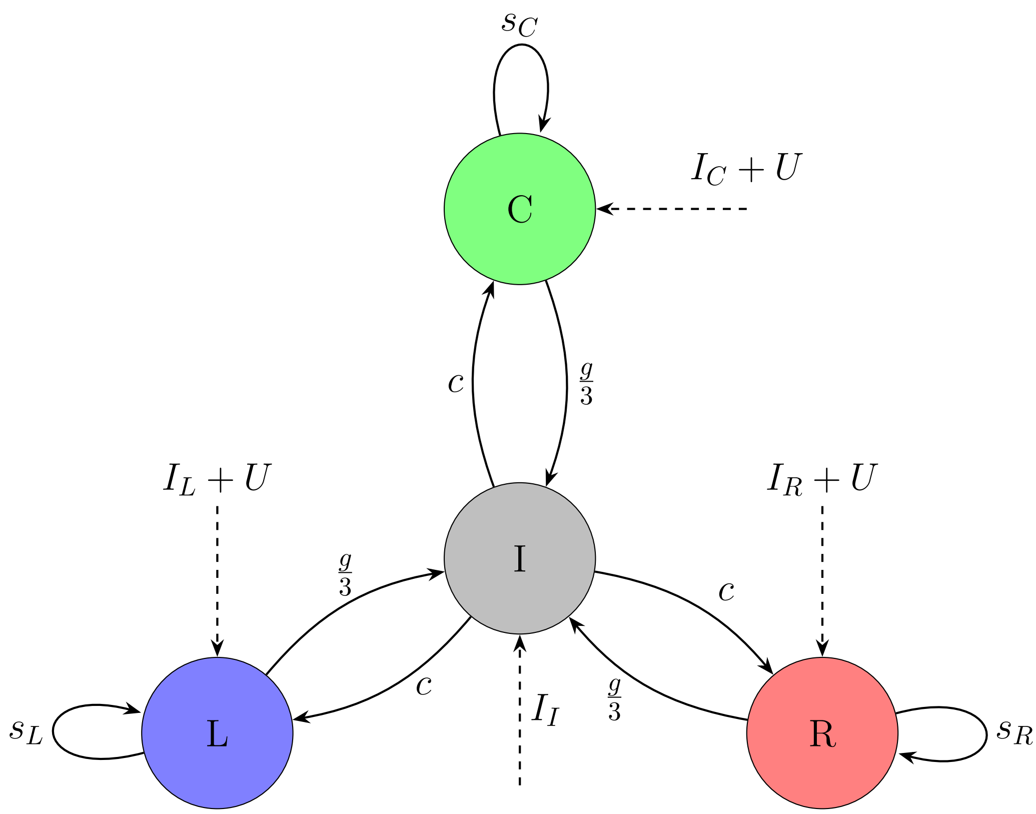

Figure 1: Schematic representation of the rate model for 3-choice tasks. The choices are represented by three excitatory populations labeled L (Left), C (Center), and R (Right), which receive external inputs (I_L, I_C, and I_R, respectively) and exhibit self-excitation with strengths s_L, s_C, and s_R. There's also an external ramping input U common to all the excitatory populations. Each excitatory population affects to an inhibitory population (I) with weight $g/3$, and the inhibitory neuron provides feedback with strength c to all excitatory populations. An external input I_I is also applied to the inhibitory neuron.

1.1 Derivation of the normal form

We assume a series expansion for the solution:

$$r_i(t) = R_i + \varepsilon\, r_{1,i}(t) + \varepsilon^2\, r_{2,i}(t) + O(\varepsilon^3), \quad i = L, C, R, \tag{7}$$

$$r_I(t) = R_I + \varepsilon\, r_{1,I}(t) + \varepsilon^2\, r_{2,I}(t) + O(\varepsilon^3). \tag{8}$$

The fixed point $R = (R_1, R_2, R_3, R_I)$ is determined at $O(1)$:

$$R_i = \phi\Big(s_i\, R_i - c\, R_I + I_i\Big), \quad i = L, C, R, \tag{9}$$

$$R_I = \phi_I\Big(\frac{g}{3}(R_L + R_C + R_R) + I_I\Big). \tag{10}$$

Additionally, we introduce a slow time scale:

$$T = \varepsilon\, t,$$

so that

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \varepsilon\, \frac{\partial}{\partial T}.$$

We define

$$X_i = s_i\, r_i - c\, r_I + I_i + U. \tag{11}$$

Substituting the expansions and using $U = \varepsilon^2\, \Delta U$, we have

$$X_i = s_i\,(R_i + \varepsilon\, r_{1,i} + \cdots) - c\,(R_I + \varepsilon\, r_{1,I} + \cdots) + I_i + \varepsilon^2\, \Delta U.$$

We then group:

- Order $O(1)$:

$$X_{i,0} = s_i\, R_i - c\, R_I + I_i.$$

- Order $O(\varepsilon)$:

$$\delta X_i^{(1)} = \varepsilon\Big[s_i\, r_{1,i} - c\, r_{1,I}\Big].$$

- Order $O(\varepsilon^2)$: includes the term $\varepsilon^2\, \Delta U$.

The Taylor expansion of ϕ about $X_{i,0}$ is

$$\phi(X_i) = \phi(X_{i,0}) + \phi'(X_{i,0})\, \delta X_i + \frac{1}{2}\, \phi''(X_{i,0})\, (\delta X_i)^2 + O(\varepsilon^3), \tag{12}$$

with

$$\delta X_i = \varepsilon\Big[s_i\, r_{1,i} - c\, r_{1,I}\Big] + \varepsilon^2\, \Delta U.$$

Thus,

$$\phi\Big(s_i\, r_i - c\, r_I + I_i + U\Big) = \phi(X_{i,0}) + \varepsilon\, \phi'(X_{i,0})\Big(s_i\, r_{1,i} - c\, r_{1,I}\Big) + \varepsilon^2\, \left(\phi'(X_{i,0})\, \Delta U + \frac{1}{2}\, \phi''(X_{i,0})\Big(s_i\, r_{1,i} - c\, r_{1,I}\Big)^2\right) + O(\varepsilon^3).$$

For the equation (5), substituting the expansion we have:

At $O(1)$:

$$R_i = \phi(X_{i,0}), \quad i = L, C, R.$$

At $O(\varepsilon)$:

$$\begin{aligned}\tau\, \frac{d}{dt}\Big(R_i + \varepsilon\, r_{1,i}\Big) &= -\Big(R_i + \varepsilon\, r_{1,i}\Big) \\ &\quad + \phi(X_{i,0}) + \varepsilon\, \phi'(X_{i,0})\Big[s_i\, r_{1,i} - c\, r_{1,I}\Big] + O(\varepsilon^2).\end{aligned} \tag{13}$$

Since $R_i = \phi(X_{i,0})$, the $O(1)$ terms cancel. Thus, dividing by ε we obtain:

$$\tau\,\dot r_{1,i} = \Big[-1 + s_i\,\phi'(X_{i,0})\Big] r_{1,i} - c\,\phi'(X_{i,0})\,r_{1,I}, \quad i = L, C, R. \tag{14}$$

The **bifurcation condition** we impose is:

$$s_i\,\phi'(X_{i,0}) = 1, \quad i = L, C, R. \tag{15}$$

Under this condition, (14) reduces to:

$$\tau\,\dot r_{1,i} = -c\,\phi'(X_{i,0})\,r_{1,I}, \quad i = L, C, R. \tag{16}$$

Similarly, linearizing the inhibitory equation (6) gives:

$$\tau_I\,\dot r_{1,I} = -r_{1,I} + \phi_I'\Big(\frac{g}{3}(R_L + R_C + R_R) + I_I\Big)\frac{g}{3}\sum_{i=L,C,R} r_{1,i}. \tag{17}$$

Then the $O(\epsilon)$ equations can be written as

$$L_0\,r_1 = 0,$$

with .

$$L_0 = \begin{pmatrix} 0 & 0 & 0 & c\,\phi'(X_{L,0}) \\ 0 & 0 & 0 & c\,\phi'(X_{C,0}) \\ 0 & 0 & 0 & c\,\phi'(X_{R,0}) \\ -\frac{g}{3}\,\phi_I'\Big(\frac{g}{3}(R_L{+}R_C{+}R_R){+}I_I\Big) & -\frac{g}{3}\,\phi_I'\Big(\frac{g}{3}(R_L{+}R_C{+}R_R){+}I_I\Big) & -\frac{g}{3}\,\phi_I'\Big(\frac{g}{3}(R_L{+}R_C{+}R_R){+}I_I\Big) & 1 \end{pmatrix}.$$

Here, $X_{i,0} = s_i\,R_i - c\,R_I + I_i$.

Due to the slow time scale $T = \varepsilon\,t$, the time derivative expands as:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \varepsilon\,\frac{\partial}{\partial T}.$$

The contribution from the slow scale (when acting on r_1) appears at order ε^2 and is grouped into the operator L_1:

$$L_1 = \begin{pmatrix} \tau\,\partial_T & 0 & 0 & 0 \\ 0 & \tau\,\partial_T & 0 & 0 \\ 0 & 0 & \tau\,\partial_T & 0 \\ 0 & 0 & 0 & \tau_I\,\partial_T \end{pmatrix}. \tag{18}$$

At order ε^2, we collect terms from the Taylor expansion (12). Recall that

$$\delta X_i = \varepsilon\Big[s_i\,r_{1,i} - c\,r_{1,I}\Big] + \varepsilon^2\,\Delta U.$$

Thus, from (12) we have:

$$\phi(X_i) = \phi(X_{i,0}) + \varepsilon\,\phi'(X_{i,0})\Big(s_i\,r_{1,i} - c\,r_{1,I}\Big) + \varepsilon^2\left(\phi'(X_{i,0})\,\Delta U + \frac{1}{2}\,\phi''(X_{i,0})\Big(s_i\,r_{1,i} - c\,r_{1,I}\Big)^2\right) + O(\varepsilon^3). \tag{19}$$

If the inputs have the form

$$I_i = I_0 + \varepsilon^2\,\bar I_i,$$

then the order ε^2 term for the ith excitatory equation is:

$$N_{2,i} = \phi'(X_{i,0})\Big(\bar{I}_i + \Delta U\Big) + \frac{1}{2}\,\phi''(X_{i,0})\Big[s_i\, r_{1,i} - c\, r_{1,I}\Big]^2. \tag{20}$$

An analogous term $N_{2,I}$ is obtained for the inhibitory equation from the expansion of ϕ_I.

Thus, the order ε^2 equation is written as

$$L_0\, r_2 + L_1\, r_1 = N_2, \tag{21}$$

Since L_0 has a nontrivial null space (by the bifurcation condition), a solution for r_2 exists only if the forcing term $N_2 - L_1\, r_1$ is orthogonal to the null space of the adjoint of L_0. Let $\{e_1, e_2\}$ be a basis for this null space, for example, we choose:

$$e_1 = (1, -1, 0, 0), \quad e_1 = (1, 1, -2, 0).$$

The **solvability condition** is given by:

$$\langle e_j,\ L_1\, r_1 - N_2\rangle = 0, \quad j = 1, 2. \tag{22}$$

Expressing the first-order solution in the form

$$r_1 = e_1\, X_1(T) + e_2\, X_2(T),$$

Where $X_1 = r_L - r_C, X_2 = r_L + r_C - 2r_R$,

The normal form equations are:

$$\tau\, \dot{X}_1 = A_1\left(\bar{I}_L - \bar{I}_C\right) + A_1\, \Delta U + C_1\, X_1\, X_2 + A_1(\xi_L(t) - \xi_C(t)) + O(\epsilon^3), \tag{23}$$

$$\tau\, \dot{X}_2 = A_2\left(\bar{I}_L + \bar{I}_C - 2\bar{I}_R\right) + A_2\, \Delta U + C_2\left(X_1^2 - 3X_2^2\right) + A_2(\xi_L(t) + \xi_C(t) - 2\xi_R(t)) + O(\epsilon^3). \tag{24}$$

Here, the coefficients are given in terms of the initial parameters as follows:

$$A_1 = \frac{1}{2}\Big[\phi'(X_{L,0}) - \phi'(X_{C,0})\Big], \qquad A_2 = \frac{1}{6}\Big[\phi'(X_{L,0}) + \phi'(X_{C,0}) - 2\,\phi'(X_{R,0})\Big],$$
$$C_1 = \frac{1}{2}\Big[s_L^2\,\phi''(X_{L,0}) - s_C^2\,\phi''(X_{C,0})\Big], \qquad C_2 = \frac{1}{6}\Big[s_L^2\,\phi''(X_{L,0}) + s_C^2\,\phi''(X_{C,0}) - 2\,s_R^2\,\phi''(X_{R,0})\Big].$$

We will consider variations of s, $s = s_0 + \epsilon^2 \bar{s}_i + O(\epsilon^3)$.

Our fixed point is now: $R = (R, R, R, R_I)$

$$X_0 = s_0 R - cR_i + I_0 + U_0 \tag{25}$$

$$\begin{aligned} X_{i,1} &= \epsilon[s_0 r_{1,i} - c r_{1,I}] \\ X_{i,2} &= \epsilon^2[s_0 r_{2,i} + R\bar{s}_i + \Delta U + \bar{I}_i] \\ X_{i,3} &= \epsilon^3[s_0 r_{3,i} + r_{1,i}\bar{s}_i] \end{aligned} \tag{26}$$

$$\Delta X_i = \epsilon[s_0 r_{1,i} - c r_{1,I}] + \epsilon^2[R\bar{s}_i + \Delta U + \bar{I}] \tag{27}$$

$$\phi(X_i) = \phi(X_0) + \phi'(X_0)(\Delta X_i) + \frac{1}{2}\,\phi''(X_0)(\Delta X_i)^2 + O(\epsilon^3) \tag{28}$$

Substituting and grouping:

$$\phi(X_i) = \phi(X_0) + \epsilon\phi'(X_0)(s_0 r_{1,i} - c r_{1,I}) + \epsilon^2 \left(\phi'(X_0)(R\bar{s}_i + \Delta U + \bar{I}_i) + \frac{1}{2}\phi''(X_0)(s_0 r_{1,i} - c r_{1,I})^2\right) + O(\epsilon^3) \quad (29)$$

In $O(1)$:

$$R = \phi(X_0)$$

$O(\epsilon)$:

$$\tau \dot{r}_{1,i} = \underbrace{(-1 + s_0\phi'(X_0))}_{0} r_{1,i} - c\phi'(X_0) r_{1,I}$$

Then, we get that

$$N_2 = \phi' \begin{pmatrix} \bar{I}_L + R\bar{s}_L + \Delta U \\ \bar{I}_C + R\bar{s}_C + \Delta U \\ \bar{I}_R + R\bar{s}_R + \Delta U \\ 0 \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \phi''(s_0 r_{L,1} - c r_{1,I})^2 \\ \phi''(s_0 r_{C,1} - c r_{1,I})^2 \\ \phi''(s_0 r_{R,1} - c r_{1,I})^2 \\ \phi_I'' \frac{g^2}{9}(r_{L,1} + r_{C,1} + r_{R,1}) \end{pmatrix}$$

At $O(\epsilon)$ we solve $L_0 r_1 = 0$. We can write the solution as $r_1 = e_1 X_1(T) + e_2 X_2(T)$

Thus, we have that:

$$r_1 = \begin{pmatrix} X_1 + X_2 \\ -X_1 + X_2 \\ -2X_2 \\ 0 \end{pmatrix}$$

For $O(\epsilon^2)$:

$$L_0 r_2 + L_1 r_1 = N_2$$

We can now rewrite N_2 in terms of X_1, X_2 as:

$$N_2 = \phi' \begin{pmatrix} \bar{I}_L + R\bar{s}_L + \Delta U \\ \bar{I}_C + R\bar{s}_C + \Delta U \\ \bar{I}_R + R\bar{s}_R + \Delta U \\ 0 \end{pmatrix} + \frac{s_0^2\phi''}{2} \begin{pmatrix} (X_1 + X_2)^2 \\ (-X_1 + X_2)^2 \\ 4X_2^2 \\ 0 \end{pmatrix}$$

1.2 Solvability conditions

If we multiply by a vector $v^T \in ker(L_0)$, we obtain:

$$v^T N_2 = \underbrace{v^T L_0 r_1}_{0} + v^T L_1 r_0 = v^T L_1 r_0$$

Thus,

$$v^T N_2 - v^T L_1 r_0 = 0 \implies < v^T, N_2 - L_1 r_0 >= 0 \implies < v^T, N_2 >= 0$$

In consequence, our solvability conditions will be:

$$\begin{aligned} \langle e_1, L_1 r_1 \rangle &= \langle e_1, N_2 \rangle \\ \langle e_2, L_1 r_1 \rangle &= \langle e_2, N_2 \rangle \end{aligned} \quad (30)$$

This results in the equations:

$$\begin{aligned} \tau\dot{X}_1 &= \frac{\phi'}{2}(\bar{I}_L - \bar{I}_C + R(\bar{s}_L - \bar{s}_C)) + s_0^2\phi''(X_1X_2) + \frac{1}{2}(\xi_L(t) - \xi_C(t)) \\ \tau\dot{X}_2 &= \frac{\phi'}{6}(\bar{I}_L + \bar{I}_C - 2\bar{I}_R + R(\bar{s}_L + \bar{s}_C - 2\bar{s}_R)) + \frac{s_0^2\phi''}{6}(X_1^2 - 3X_2^2) + \frac{1}{6}(\xi_L(t) + \xi_C(t) - 2\xi_R(t)) \end{aligned} \tag{31}$$

We can think of this equations as the field in $\mathbb{R}^2$, $F(X_1, X_2) = (F_1, F_2) = (\bar{F}_1, 3\bar{F}_2)$, where

$$\begin{aligned} \bar{F}_1 &= \frac{\phi'}{2}(\bar{I}_L - \bar{I}_C + R(\bar{s}_L - \bar{s}_C)) + s_0^2\phi''(X_1X_2) \\ \bar{F}_2 &= \frac{\phi'}{6}(\bar{I}_L + \bar{I}_C - 2\bar{I}_R + R(\bar{s}_L + \bar{s}_C - 2\bar{s}_R)) + \frac{s_0^2\phi''}{6}(X_1^2 - 3X_2^2) \end{aligned}$$

The field defined by this equations is irrotational as:

$$\begin{aligned} \frac{\partial\bar{F}_1}{\partial y} &= X_1\phi'' s_0^2 \\ \frac{\partial\bar{F}_2}{\partial x} &= \frac{X_1\phi'' s_0^2}{3} \end{aligned} \tag{32}$$

In consequence, it exists a potential ψ such that $\frac{\partial\psi}{\partial x} = F_1$, $\frac{\partial\psi}{\partial y} = F_2$:

$$\psi(X_1, X_2) = \frac{1}{2}(X_1^2X_2\phi'' s_0^2 - X_1\phi'\left(I_C - I_L + R(s_C - s_L)\right) - X_2^3\phi'' s_0^2 + X_2\phi'\left(I_C + I_L - 2I_R + R(s_C + s_L - 2s_R)\right))$$

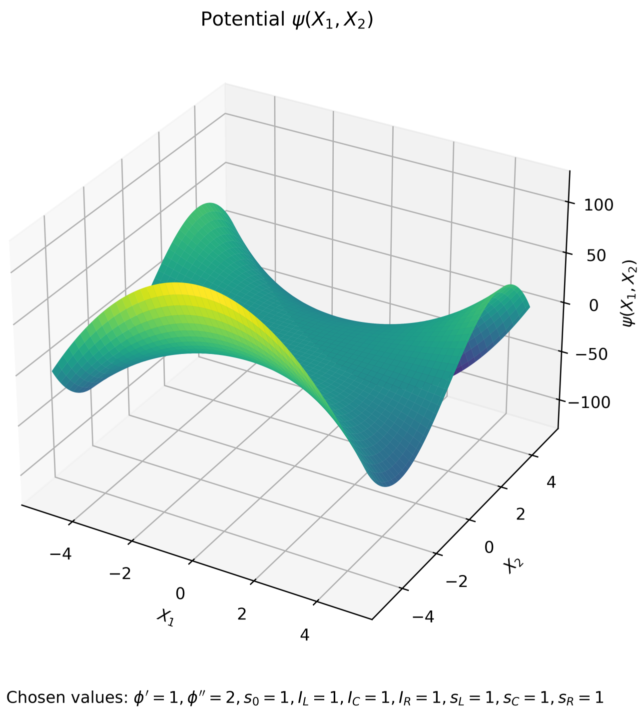

Figure 2: Potential obtained from the order 2 normal equations.

We can go up to third order to obtain more terms in this potential:

Now, r_2 has components in the directions $e_c = \big(1, 1, 1, 0\big)$ and $e_I = \big(0, 0, 0, 1\big)$.

Taking $r_2 = e_C R_{2C} + e_I R_{2I}$:

$$r_2 = \begin{pmatrix} R_{2C} \\ R_{2C} \\ R_{2C} \\ R_{2I} \end{pmatrix}$$

Projecting the equations:

$$\begin{aligned} \langle e_c, L_0 r_2 \rangle &= \langle e_c, N_2 \rangle \\ \langle e_I, L_0 r_2 \rangle &= \langle e_I, N_2 \rangle \end{aligned} \tag{33}$$

Then as,

$$L_0 r_2 = \left(c\phi' R_{2I}, c\phi' R_{2I}, c\phi' R_{2I}, -g\phi'_I R_{2C} + R_{2I} \right)$$

We obtain the system of equations:

$$\begin{aligned} 3c\phi' R_{2I} &= \phi'(\bar{I}_L + \bar{I}_C + \bar{I}_R + R(\bar{s}_L + \bar{s}_C + \bar{s}_R) + 3\Delta U) + \frac{s_0^2 \phi''}{2} \left(2X_1^2 + 6X_2^2 \right) \\ -g\phi' R_{2C} + R_{2I} &= 0 \end{aligned} \tag{34}$$

Isolating, we find:

$$R_{2C} = \frac{1}{g\phi'_I} R_{2I} \qquad R_{2I} = \frac{1}{3c}(\bar{I}_L + \bar{I}_C + \bar{I}_R + R(\bar{s}_L + \bar{s}_C + \bar{s}_R) + 3\Delta U) + \frac{s_0^2 \phi''}{3c\phi'}(X_1^2 + 3X_2^2)$$

Including r_2 and the terms O(ϵ^3) in ΔX_i:

$$\Delta X_i = \epsilon[s_0 r_{1,i} - c r_{1,I}] + \epsilon^2 [R\bar{s}_i + s_0 r_{2,i} - c r_{2,I} + \Delta U + \bar{I}] + \epsilon^3 [r_{1,i} \bar{s}_i] \tag{35}$$

The $O(\epsilon^3)$ term in the Taylor expansion of $\phi(X_i)$ is:

$$\epsilon^3 \left(\phi'(r_{1,i}\bar{s}_i) + \phi''(s_o r_{1,i} - c r_{1,I})(R\bar{s}_i + s_0 r_{2,i} - c r_{2,I} + \Delta U + \bar{I}_i) + \frac{1}{6}\phi'''(s_o r_{1,i} - c r_{1,I})^3 \right) \tag{36}$$

Now, the equations up to $O(\epsilon^3)$ are:

$$L_0 r_3 + L_1 r_2 = N_3$$

Where,

$$N_3 = \phi' \begin{pmatrix} \bar{s}_L(X_1 + X_2) \\ \bar{s}_C(-X_1 + X_2) \\ \bar{s}_R(-2X_2) \\ 0 \end{pmatrix} + \phi'' s_0 \begin{pmatrix} (X_1 + X_2)(R\bar{s_L} + \underbrace{s_0 R_{2C} - c R_{2I}}_{(s_0 - cg\phi'_I)R_{2C}} + \Delta U + \bar{I}_L) \\ (-X_1 + X_2)(R\bar{s_C} + (s_0 - cg\phi'_I)R_{2C} + \Delta U + \bar{I}_C) \\ (-2X_2)(R\bar{s_R} + (s_0 - cg\phi'_I)R_{2C} + \Delta U + \bar{I}_R) \\ 0 \end{pmatrix} + \frac{\phi''' s_0^3}{6} \begin{pmatrix} (X_1 + X_2)^3 \\ (-X_1 + X_2)^3 \\ -8X_2^3 \\ 0 \end{pmatrix}$$

Applying the solvability conditions, we obtain the equations:

$$0 = \langle e_1, N_3 \rangle \quad 0 = \langle e_2, N_3 \rangle \tag{37}$$

Thus,

$$s_0 \phi'' \tag{38}$$