

# Kinematics and Dynamics of a Continuum Motion-Correction Mechanism for Frameless and Maskless Cancer Radiation Therapy

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**Abstract**—We present the analysis of the kinematics and contact dynamics between the soft actuators and a patient’s head in the real-time motion compensation in robotic cancer radio-surgery. Here, we analyze the forces that govern the interaction between the soft robots and the head and neck region of the patient in cranial frameless and maskless radiosurgery. Relating the boundary value problem solutions of the stress and forces that govern the deformation of each IAB to the contact forces on the patient’s head, we derive the manipulation map for a desired head motion correction and construct the associated Jacobian for realizing desired particular motions. This is a work in progress and suggestions are welcome.

## I. INTRODUCTION

In 2019, an estimated 1,762,450 new cases of cancer will be diagnosed in the United States and 606,880 people will die from the disease. The burden of cancer care is financially significant with estimated national expenditures \$147.3 billion in 2017 [1]. Along with surgery and chemotherapy, radiation therapy (RT) is an essential part of a successful cancer treatment, with more than 50% of all patients receiving RT for the management of their cancers. There have been steady gains in the five-year survival rate for cancer patients, with an improvement of 66% across all cancer types. The increase in survival rate has been attributed in a large part to technological advancements in RT. RT can now tightly conform the radiation dose to the 3D shape of a tumor with approximately 1-2 mm accuracy. This allows for further dose escalation to the tumor, while minimizing dose to nearby healthy organs-at-risk (OAR), and has had significant impact on cancer patients in terms of better tumor control and normal tissue sparing. Unfortunately, RT is currently considered as a static process, whereby treatment plans are calculated based on a snapshot (initial CT scan) of the patient anatomy prior to treatment, and then delivered over the course of a number of weeks. This assumption, that the patient’s internal anatomy maintains the same position as in the initial CT snapshot over the entire course of treatment is incorrect, and is not compatible with modern RT technology, which can now target radiation dose to the tumor at the millimeter level. Issues involving internal anatomic motion during treatment have become ever

more critical to address, and currently limit the potential of modern RT. As an example, for prostate cancer, even with the correct initial patient setup at the linear accelerator (LINAC), the prostate can undergo a wide variety of motions once RT has started, with sudden excursions beyond target in excess of 10mm taking place within a few seconds. As the prostate is located directly between the bladder and rectum, such motion can lead to incomplete prostate irradiation and unwanted irradiation of the bladder, urethra, rectum, erectile tissues, or sphincters resulting in serious health issues such as incontinence, rectal leakage, or other tissue toxicity [2].

This work is a continuation of the model verified in [3] for use in real-time motion compensation/correction in radiation therapy. Here, we present the systematic analysis of the parallel continuum mechanism which manipulate the head and neck (H&N) region of a patient during cranial radiosurgery or radiation therapy. Having a real-time closed-loop robotic system that can automatically correct motion deviation, particularly during beam-on time during is an RT technological need that has the potential benefits of hastening the current treatment time in clinics, minimizing patient discomfort post-treatment (as opposed to rigid frames and masks used in frame and mask-based RT), and drastically improving dose efficacy so that the patient’s treatment can be effectively fractionated. For details on the radiation oncological treatment procedure, we refer readers to [4] and [5].

We call the individual soft robots inflatable air bladders (IABs) owing to their hollow internal chambers that admit or eject air based on an applied internal pressurization. We make the fundamental assumption that the IAB’s deformation follows the isochoric deformation principle, with reasonable local volume preservation during deformation constraints baked into the physical IAB material properties. We derive the manipulator map, kinematics, Jacobian and end-effector velocities. Soft robots are notoriously difficult to control, given their continuum-based mechanical properties, and the interdependency of the parameters that characterize their deformation. It is not surprising that different schemes for controlling soft continuum robots have appeared in literature with mixed successes [6]–[12]. For an extensive literature review of the control of continuum soft robots, we refer readers to [13].

The soft robot mechanism presented in this work consists of IABs connected with extensible couplings; these couplings are chosen to exploit the soft structures’ design for impedance control of the H&N region of the patient. We analyze the manipulation map, the Jacobian of the IAB chains, as well

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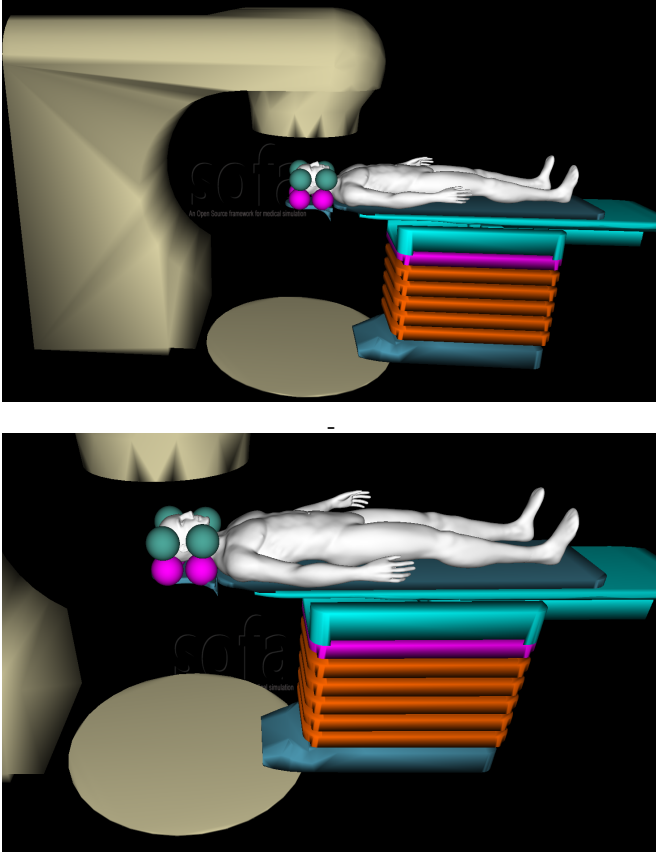


Fig. 1. System setup in the SOFA Framework Architecture. **Top:** Gantry, Turntable, Patient and IAB Chains around the patient's H&N Region. **Bottom:** Close-up view of compensating IABs around patient's H&N region with the patient lying in a supine position on the treatment couch. [Image best visualized in colored ink].

as the contact equations between the IAB mechanism system and patient's cranial region. This paper is a sequel to our previous works [4], [7], [14]–[16]; additionally, we expand upon the kinematics and dynamics of the multi-DOF soft actuation system for H&N motion compensation in RT. Our design goals include a system that (1) provides patient comfort whilst manipulating human body parts necessary for trajectory following during RT, (2) assures dose efficacy while not attenuating the ionizing radiation dose treatment due to undesirable material properties (3) capable of emerging complex morphological computational behavior with deformable soft robots – simplifying complex patient motion planning and control during robotic RT treatment.

The rest of this paper is organized as follows: we analyze the contact kinematics in § II, describing the contact model, and how we solve the boundary value problem for the IABs' deformation. In § III, we derive the mechanism's end-effector velocities and forces, and then derive the Newton-Euler Lagrangian relationship in § IV. We present manipulation examples in the SOFA framework in § VI and conclude the paper in § VII. Proofs and derivations are provided in appendices A, B, and C.

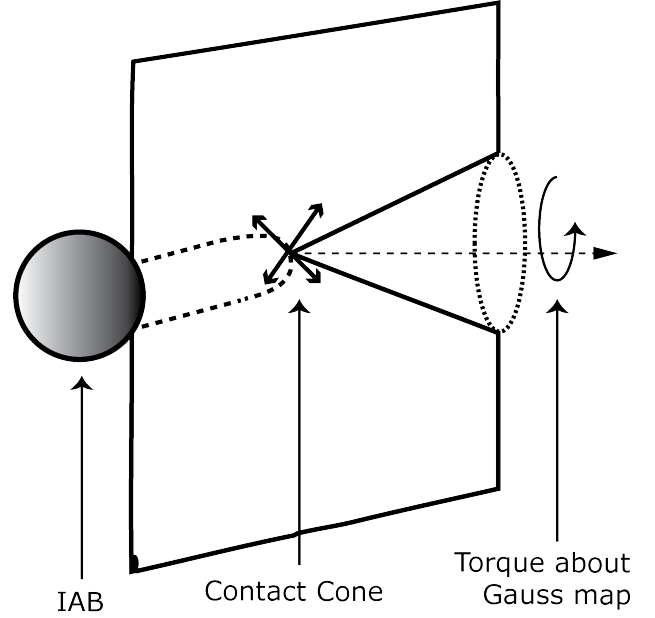


Fig. 2. Illustration of the IAB Soft Contact Type

## II. ANALYSIS OF CONTACT KINEMATICS

The manipulators and head are considered as linear elastic object materials with the interaction at the head and an IAB contact considered as a classical case of two elastic bodies in contact. We model the contact type between the head and an IAB similar to the soft finger contact primitive of [17]. Here, our soft contact is the convex sum of *point contacts* with friction over the small area of contact. IAB forces and torques are modeled within a “cone of forces” about the direction of the surface normal from a patient's head (see Figure 2). The trajectory of the head under the influence of motion of an IAB is influenced by the position vector  $\mathbf{r}$  described in [3]. When the IAB deforms, body forces over its current configuration and contact (*traction*) forces over its boundary  $\partial\mathcal{B}$  impact motion on the head. Constrained by the frictional coefficient, we define the soft contact force inside the friction cone as

$$\tilde{\mathbf{F}}_{c_i} = \begin{bmatrix} \mathbf{I} & 0 \\ 0 & n_{c_i} \end{bmatrix} \begin{bmatrix} f_{c_i} \\ \tau_{c_i} \end{bmatrix}, \quad (1)$$

where  $f_{c_i} \in \mathbb{R}^3$  denotes the amount of force exerted by the IAB along the direction of contact,  $\tau_{c_i} \in \mathbb{R}$  is the moment of the contact force, and  $n_{c_i}$  is the *normal* or *Gauss map*<sup>1</sup> for a manifold  $S \subset \mathbb{R}^3$  of a head surface. For contact models with friction, we require that all contact forces lie within the friction cone, determined by the frictional coefficient. The set of forces within or on the boundary of the friction cone is

$$FC = \{f_c \in \mathbb{R}^n : \|f_{c_{ij}}^t\| \leq \mu_{ij} \|f_{c_i}^n\|, \\ i = 1, \dots, k, j = 1, \dots, m_i\} \quad (2)$$

where  $f_{c_{ij}}^t$  is the tangent component of the  $j^{th}$  element of the contact force,  $f_{c_i}^n$  is  $i^{th}$  contact's normal force, and  $\mu_{ij}$  is  $f_{c_{ij}}$ 's coefficient of friction.

<sup>1</sup>A normal map for a manifold  $S$  is a continuous map  $g : S \rightarrow S^2 \subset \mathbb{R}^3$  such that for every  $s \in S$ ,  $g(s)$  is orthogonal to  $S$  at  $s$  [18].

### A. Boundary Value Problem for IAB Deformation

We now solve the boundary-value problem for the IAB deformation when in contact with the head as a follow-up to our analysis in [3]. Again, we assume a spherically-symmetric deformation constraint imposed on the IAB when the head rolls or slips. This may be achieved via an appropriate vulcanization of the IAB rubber material, for example (see [19] or [20]). For an IAB material, when the SoRos are in contact with the head, the applied forces on the current configuration of the IAB body  $\mathcal{B}$  are

- the body forces,  $\mathbf{b}$
- the contact forces,  $\mathbf{f}_c$ , at the IAB boundary,  $\partial\mathcal{B}$ , and
- the gravitational force of the head mass acting along the direction of contact,  $\mathbf{f}_g$ .

We make the explicit assumption that the head maintains contact with the IAB throughout deformation. This is a reasonable assumption given the kinematic arrangement of ???. Suppose that for the  $i^{\text{th}}$  IAB in the chain,  $\mathbf{r}_{c_i}$  represents the direction vector perpendicular from the point of contact to the center of the head cone of forces, it follows that the three equations that govern the motion of the IAB continuum are given as

$$\dot{\rho} + \rho \operatorname{div} \mathbf{v} = 0 \quad (3a)$$

$$\boldsymbol{\sigma}^T = \boldsymbol{\sigma} \quad (3b)$$

$$\operatorname{div} \boldsymbol{\sigma}^T + \rho \mathbf{b} = \rho \dot{\mathbf{v}}, \quad (3c)$$

being respectively the conservation of mass (3a), the symmetry of the stress tensor (3b), and the balance of linear momentum respectively, (see [21, pp. 150], for the derivation). In general, we expect that the mass of the body will be conserved given the incompressibility assumption of the IAB material, thus guaranteeing that (3a) is fulfilled. We have from (3c) and the symmetric properties of the stress tensor that

$$\begin{aligned} \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \sigma_{rr}) + \frac{1}{r \sin \phi} \frac{\partial}{\partial \phi} (\sin \phi \sigma_{r\phi}) + \frac{1}{r \sin \phi} \frac{\partial}{\partial \theta} (\sigma_{r\theta}) \\ - \frac{1}{r} (\sigma_{\theta\theta} + \sigma_{\phi\phi}) + \rho b_r = \rho \ddot{r}_x \end{aligned} \quad (4a)$$

$$\begin{aligned} \frac{1}{r^3} \frac{\partial}{\partial r} (r^3 \sigma_{r\phi}) + \frac{1}{r \sin \phi} \frac{\partial}{\partial \phi} (\sin \phi \sigma_{\phi\phi}) + \frac{1}{r \sin \phi} \frac{\partial}{\partial \theta} (\sigma_{\theta\phi}) \\ - \frac{\cot \phi}{r} (\sigma_{\theta\theta}) + \rho b_\phi = \rho \ddot{r}_y \end{aligned} \quad (4b)$$

$$\begin{aligned} \frac{1}{r^3} \frac{\partial}{\partial r} (r^3 \sigma_{r\theta}) + \frac{1}{r \sin^2 \phi} \frac{\partial}{\partial \phi} (\sin^2 \phi \sigma_{\theta\phi}) \\ + \frac{1}{r \sin \phi} \frac{\partial}{\partial \theta} (\sigma_{\theta\theta}) + \rho b_\theta = \rho \ddot{r}_z \end{aligned} \quad (4c)$$

where  $\ddot{r}_x$ ,  $\ddot{r}_y$ , and  $\ddot{r}_z$  are components of the position vector  $\ddot{\mathbf{r}}$  as defined in § A and the body forces  $b_r$ ,  $b_\phi$ ,  $b_\theta$  are components of the gravitational force of the head acting on the IAB body  $\mathcal{B}$ . If the deformation is spherically symmetric, we expect that the shear stress component contributions  $\sigma_{r\phi}$ ,  $\sigma_{r\theta}$ ,  $\sigma_{\phi\theta}$  would vanish in (4). It follows that the forces on the head (see derivation in Appendix § A) are in part the internal

pressurization, and component stresses  $\{P_i, \sigma_{\phi\phi}(\epsilon), \sigma_{\theta\theta}(\zeta)\}$  as given in (5)

$$\begin{aligned} P = \int_{r_i}^{r_o} \left[ \frac{1}{r} \left( -2p + 2C_1 \frac{r^2}{R^2} - 2C_2 \frac{R^8}{r^8} \right) - \rho b_r \right. \\ \left. + \rho \cos \theta \left( 2\dot{r}\dot{\phi} \cos \theta + r \cos \theta \ddot{\phi} - 2r\dot{\theta}\dot{\phi} \sin \theta \right) - \rho \sin \phi \right. \\ \left. \left( \cos \theta (-\ddot{r} + r\dot{\theta}^2 + r\dot{\phi}^2) + \sin \theta (2\dot{r}\dot{\theta} + r\ddot{\theta}) \right) \right] dr \end{aligned} \quad (5a)$$

$$\begin{aligned} \sigma_{\phi\phi}(\epsilon) = - \int_{\epsilon}^{\pi} \left[ r \rho \left[ \cos \phi \left( 2r\dot{\theta}\dot{\phi} \cos \theta + (2\dot{r}\dot{\phi} + r\ddot{\phi}) \sin \theta \right) \right. \right. \\ \left. \left. + \sin \theta \left( 2\dot{r}\dot{\phi} \cos \theta + r\ddot{\phi} \cos \theta + (\ddot{r} - r\dot{\theta}^2 - r\dot{\phi}^2) \right) \sin \phi \right] \right. \\ \left. - \rho r b_\theta \right] d\phi, \quad 0 \leq \epsilon \leq \pi \end{aligned} \quad (5b)$$

$$\begin{aligned} \sigma_{\theta\theta}(\zeta) = - \int_{\zeta}^{2\pi} \left[ -r \rho b_\theta \sin \phi + r \rho \sin \phi \cos \phi \left( \ddot{r} - r\dot{\phi}^2 \right) \right. \\ \left. - r \rho \sin^2 \phi \left( 2\dot{r}\dot{\phi} + r\ddot{\phi} \right) \right] d\theta, \quad 0 \leq \zeta \leq 2\pi, \end{aligned} \quad (5c)$$

where  $0 \leq \epsilon \leq \pi$ , and  $0 \leq \zeta \leq 2\pi$ .

### B. Contact Forces, IAB Stress Components, and Head Gravitational Force

Here, we relate the microscopic contact stress of the previous section with the macroscopic descriptions of the contact friction to enable us treat different material combinations for the manipulator and head. We assume that the stress vector  $\boldsymbol{\sigma}$  at a point on the IAB surface is uniform and continuous throughout the IAB boundary so that it linearly depends on the normal map (this follows from Cauchy's theorem; readers may see the proof in [21, §3.3.1]). Recall that the correspondence between material line,  $\{\mathbf{dX}, \mathbf{dX}\}$ , elements in the reference and current configuration is

$$\mathbf{dx} = \mathbf{F} \mathbf{dX} \implies \mathbf{F}^{-T} \mathbf{dx} = \mathbf{dX}. \quad (6)$$

where  $\mathbf{F}$  is the deformation gradient. Let  $\mathbf{H} = \mathbf{F}^{-T}$  and  $\mathbf{dA}$  represent an infinitesimal vector element on the material surface at a neighborhood of point  $\mathbf{X}$  in  $\mathcal{B}$  such that  $\mathbf{dA} = \mathbf{N} dA$ , where  $\mathbf{N}$  is the unit outward normal to the IAB boundary  $\partial\mathcal{B}_0$  in the reference configuration. The corresponding deformed surface of the IAB with normal  $\mathbf{n}$  from a surface,  $da$ , of the IAB in the current configuration is  $\mathbf{da} = \mathbf{n} da$ . Using Nanson's formula, we have the following relation between surfaces in the reference and current configuration

$$\mathbf{da} = J \mathbf{H} \mathbf{dA} \implies \mathbf{n} da = J \mathbf{H} \mathbf{N} dA. \quad (7)$$

where  $J = \det \mathbf{F}$ . Multiplying throughout equation (7) by the derived constitutive relation between the stress-strain relationship of [3], the resultant contact force on the boundary  $\partial\mathcal{B}$  in the current configuration may be written as (owing to the volume preservation on the boundary of the IAB material)

$$\int_{\partial\mathcal{B}} \boldsymbol{\sigma} \mathbf{n} da = \int_{\partial\mathcal{B}_0} J \boldsymbol{\sigma} \mathbf{H} \mathbf{N} dA. \quad (8)$$

We may define the Piola-Kirchhoff stress tensor field as

$$\mathbf{S} = J \mathbf{H}^T \boldsymbol{\sigma} \quad (9)$$

so that the force on an element surface  $da$  of the IAB in a configuration  $\mathcal{B}$  is

$$\sigma da = \mathbf{S}^T d\mathbf{A}.$$

Thus, the contact force  $f_{c_i}$  on the boundary  $\partial\mathcal{B}$  of the  $i^{th}$  IAB in a configuration  $\mathcal{B}$  (as in (1)) is

$$f_{c_i} = \mathbf{S}_i^T d\mathbf{A}_i = J_i \sigma_i \mathbf{H}_i d\mathbf{A}_i = J_i \sigma_i \mathbf{F}_i^{-1} d\mathbf{A}_i \quad (10)$$

where (10) follows from the symmetric property of  $\mathbf{F}_i$  and  $\sigma_i$ . For the  $i^{th}$  IAB, at the region of contact, we have the contact force as

$$f_{c_i} = J_i \left( \frac{R_i^2}{r_i^2} P_i + \frac{R_i}{r_i} \sigma_{\phi\phi_i}(\epsilon) + \frac{R_i}{r_i} \sigma_{\theta\theta_i}(\zeta) \right) d\mathbf{A}_i \quad (11)$$

where  $\sigma_{jj_i}(v)$  are the definite integrals of (5). Owing to the isochoric deformation assumption, we have from (11) that

$$f_{c_i} = \left( \frac{R_i^2}{r_i^2} P_i + \frac{R_i}{r_i} \sigma_{\phi\phi_i}(\epsilon) + \frac{R_i}{r_i} \sigma_{\theta\theta_i}(\zeta) \right) n_{c_i} dA_i. \quad (12)$$

where we have set the outward normal map  $\mathbf{N}$  to  $n_{c_i}$  of (1). The torque is the moment of the contact force on the  $i^{th}$  IAB, and it is given by

$$\tau_{c_i} = f_{c_i} \times r_{c_i} \quad (13)$$

where  $r_{c_i} \in \mathbb{R}^3$  is the unit vector between the head reference point and the contact. The soft contact force of (1) can be re-stated in terms of the derived stress tensor, the deformation gradient (see [3]) and the Piola-Kirchoff stress field of (9) *i.e.*

Friction Cones' Contact Force

$$\tilde{F}_{c_i} = \begin{bmatrix} \mathbf{I} & 0 \\ 0 & n_{c_i} \end{bmatrix} \begin{bmatrix} f_{c_i} \\ f_{c_i} \times r_{c_i} \end{bmatrix}. \quad (14)$$

where  $f_{c_i}$  and  $\tau_{c_i}$  are as given in equations (12) and (13).

### C. Contact Coordinates and Head Velocity

The head will make contact with the IAB at multiple points on its surface, so we describe the kinematics of these contact points using an atlas<sup>2</sup> of contact coordinate charts. In this sentiment, let  $C_{r_1}$  and  $C_{r_h}$  respectively represent a fixed reference frame with respect to the IAB and head,  $H$  (see Figure 3). Furthermore, let  $S_1 \subset \mathbb{R}^3$  and  $S_h \subset \mathbb{R}^3$  denote the respective *orientable manifold*<sup>3</sup> embeddings of the IAB and head surfaces with respect to frames  $C_{r_1}$  and  $C_{r_h}$ . We shall let  $S_1$  and  $S_r$  belong to the *atlases*  $\{S_{1_i}\}_{i=1}^{n_1}$ ,  $\{S_{h_i}\}_{i=1}^{n_h}$  respectively. Suppose  $(f_1, U_1)$  and  $(f_r, U_r)$  are *coordinate systems* for the IAB and the head respectively, where  $f_i$  is an invertible map,  $f_i(u_i, v_i) : U \rightarrow S_i \subset \mathbb{R}^3$

$$f_i(u_i, v_i) : \{U \rightarrow S_i \subset \mathbb{R}^3 | i = 1, h\},$$

from an open subset  $U$  of  $\mathbb{R}^2$  to a *coordinate patch*  $S_i \subset \mathbb{R}^3$  such that the partial derivatives  $\frac{\partial f_i}{\partial u_i}$  and  $\frac{\partial f_i}{\partial v_i}$  are linearly

<sup>2</sup>An atlas  $\tilde{S}$  is a set of surfaces where each surface  $S \in \tilde{S}$  has an invertible map  $f(u)$  from an open subset  $U$  of  $\mathbb{R}^2$  to a surface  $S \subset \mathbb{R}^3$  such that the partial derivatives  $\frac{\partial f}{\partial u}(\mathbf{u})$ ,  $\frac{\partial f}{\partial v}(\mathbf{v})$  are linearly independent for all  $\mathbf{u} = (u, v) \in U$ .

<sup>3</sup>An orientable manifold is a manifold  $S$  for which the Gauss map exists.

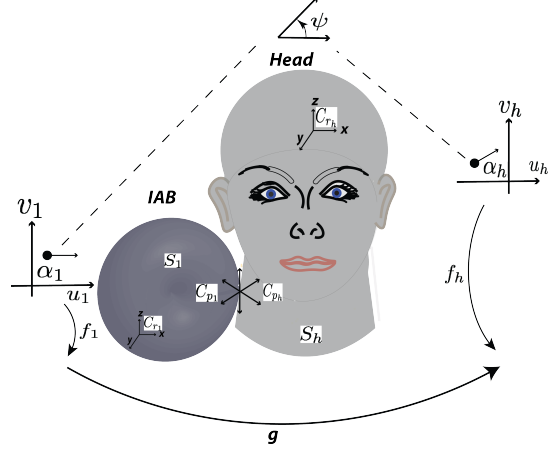


Fig. 3. Sliding and rolling contact illustration of a single IAB and the Head. [Image best visualized in colored ink].

independent. Let  $p_1(t) \in S_1$  and  $p_h(t) \in S_h$  represent the positions of the contact points with respect to frames  $C_{r_1}$  and  $C_{r_h}$  respectively at time  $t$ . In general, the contact points  $p_1(t)$  and  $p_h(t)$  will not remain in the coordinate systems  $S_1$  and  $S_h$  for all time. Thus, we choose an interval  $I$  where  $p_1(t) \in S_{1_i}$  and  $p_h(t) \in S_{h_j}$  for all  $t \in I$  and some  $i$  and  $j$ . As seen in Figure 3,  $C_{p_1}$  and  $C_{p_h}$  denote the contact frames that coincide with the *normalized Gauss frames* at  $p_1$  and  $p_h$  for all  $t \in I$ , and  $\alpha_1, \alpha_h$  are local coordinate frames that describe the IAB motion with respect to the head such that

$$\alpha_1 = (u_1, v_1) \in U_1, \text{ and } \alpha_h = (u_h, v_h) \in U_h. \quad (15)$$

Let the angle between the tangent planes of  $\alpha_1$  and  $\alpha_h$  be  $\psi$ . The transformation matrix  $g \in \Omega \subset SE(3)$  encodes the relative orientation and position of the IAB with respect to the head where  $\Omega$  is the set of all relative positions and orientations in the atlases  $\{S_{1_i}\}_{i=1}^{n_1}$ ,  $\{S_{h_i}\}_{i=1}^{n_h}$  for which the IAB and head remain in contact. We let the *contact coordinates* be described by  $\eta = (\alpha_1, \alpha_h, \psi)$ . The head's motion is governed by traction forces arising from the friction tangential to the IAB surface and the pressure normal to the IAB surface. Thus, at the points of contact, if  $R \in SO(3)$  is the rotatory component of  $g$ ,  $\eta$  must satisfy

$$g \circ f_1(\alpha_1) = f_h(\alpha_h) \quad (16a)$$

$$R n_1(\alpha_1) = -n_h(\alpha_h) \quad (16b)$$

since the contact locations must coincide for the IAB and the head, and the tangent planes must coincide so that the outward normal maps  $n_1 : S_1 \rightarrow S^2 \subset \mathbb{R}^3$  and  $n_h : S_h \rightarrow S^2 \subset \mathbb{R}^3$  agree. Furthermore, the orientation of the tangent planes of  $\alpha_1$  and  $\alpha_h$  is the unique angle  $\psi \in [0, 2\pi)$  between the  $x$ -axes of  $C_{p_1}$  and  $C_{p_h}$  such that

$$R \frac{\partial f_1}{\partial \alpha_1} M_1^{-1} R_\psi = \frac{\partial f_h}{\partial \alpha_h} M_h^{-1} \quad (17)$$



where  $M_i$  is a  $2 \times 2$  square root of the Riemannian metric tensor [22] that normalizes the columns of  $\frac{\partial f}{\partial \alpha}$ , *i.e.*

$$M_i = \begin{bmatrix} \|\frac{\partial f_i}{\partial u_i}\| & 0 \\ 0 & \|\frac{\partial f_h}{\partial v_i}\| \end{bmatrix} \quad (18)$$

and  $R_\psi$  is chosen such that a rotation of  $C_{p_1}$  about its  $z$ -axis through  $-\psi$  radians aligns the  $x$ -axes of the local coordinate system  $\alpha_1$  to that of the head's local coordinate system  $\alpha_h$  *i.e.*

$$R_\psi = \begin{bmatrix} \cos \psi & -\sin \psi \\ -\sin \psi & -\cos \psi \end{bmatrix} \quad (19)$$

with the special property that  $R_\psi = R_\psi^T = R_\psi^{-1}$ . We define the normalized Gauss frame at a point  $u$  on the surface  $U$  of the orthogonal coordinate system  $(f, U)$  as,

$$[x_u \ y_u \ z_u] = [\frac{\partial f}{\partial u} / \|\frac{\partial f}{\partial u}\| \ \frac{\partial f}{\partial v} / \|\frac{\partial f}{\partial v}\| \ n_u(f(u))] \quad (20)$$

where  $x_u$ ,  $y_u$ , and  $z_u$  are functions mapping  $U \subset \mathbb{R}^2 \rightarrow \mathbb{R}^3$  and  $n_u$  is the continuous Gauss map  $n_u : S \rightarrow S^2 \subset \mathbb{R}^3$ . The motion of the contacts  $\dot{\eta}$  as a function of components of the twist vector  $\hat{\xi} = (v, \omega)^T$  is given in (21) as the respective *first*, *second*, and *third equations of contact*. Our derivation, which closely follows [23]'s multi-fingered kinematics' proof, may be found in Appendix B.

$$\dot{\alpha}_h = M_h^{-1}(\mathcal{K}_h + \tilde{\mathcal{K}}_1)^{-1}(\omega_t - \tilde{\mathcal{K}}_1 v_t) \quad (21a)$$

$$\dot{\alpha}_1 = M_1^{-1}R_\psi(\mathcal{K}_h + \tilde{\mathcal{K}}_1)^{-1}(\omega_t - \mathcal{K}_h v_t) \quad (21b)$$

$$\dot{\psi} = \omega_n + T_h M_h \dot{\alpha}_h + T_1 M_1 \dot{\alpha}_1 \quad (21c)$$

where

$$\begin{aligned} T_h &= y_h^T \frac{\partial x_h}{\partial \alpha_h} M_h^{-1}, \quad T_1 = y_1^T \frac{\partial x_1}{\partial \alpha_1} M_1^{-1}, \\ \mathcal{K}_h &= [x_h^T, \ y_h^T]^T \frac{\partial n_h^T}{\partial \alpha_h} M_h^{-1}, \quad \omega_n = z_h^T \omega \\ \mathcal{K}_1 &= R_\psi [x_1^T, \ y_1^T]^T \frac{\partial n_1^T}{\partial \alpha_1} M_1^{-1} R_\psi, \\ \omega_t &= [x_h^T, \ y_h^T]^T [n_h \times \omega]^T, \\ v_t &= [x_h^T, \ y_h^T]^T [(-f_h \times \omega + v)]^T. \end{aligned} \quad (22)$$

Note that  $\omega_t$  is the rolling velocity of the head projected onto the tangent plane of the contact and  $v_t$  is the sliding velocity;  $\omega_n$  is the relative rotational velocity projected to the contact's surface normal, and  $\tilde{\mathcal{K}}_1 = R_\psi \mathcal{K}_1 R_\psi$  is the curvature of the IAB with respect to the contact frame that coincides with the normalized Gauss frame at  $p_1(t)$ . The matrix  $(\mathcal{K}_h + \tilde{\mathcal{K}}_1)^{-1}$  is the so-called *relative curvature* originally coined by [18]. Simplifying (22), we find that

$$\begin{aligned} x_h &= \frac{\partial f}{\partial u_h} / \|\frac{\partial f}{\partial u_h}\|, \quad y_h = \frac{\partial f}{\partial v_h} / \|\frac{\partial f}{\partial v_h}\|, \quad z_h = n_u(f(u)) \\ T_h &= y_h \left[ \frac{\partial x_h^T}{\partial u_h} / \|\frac{\partial f}{\partial u_h}\|, \frac{\partial x_h^T}{\partial v_h} / \|\frac{\partial f}{\partial v_h}\| \right], \\ T_1 &= y_1 \left[ \frac{\partial x_1^T}{\partial u_1} / \|\frac{\partial f}{\partial u_1}\|, \frac{\partial x_1^T}{\partial v_1} / \|\frac{\partial f}{\partial v_1}\| \right], \\ \mathcal{K}_h &= [x_h^T, \ y_h^T]^T \left[ \frac{\partial n_h^T}{\partial u_h} / \|\frac{\partial f}{\partial u_h}\|, \frac{\partial n_h^T}{\partial v_h} / \|\frac{\partial f}{\partial v_h}\| \right], \\ \mathcal{K}_1 &= [x_1^T, \ y_1^T]^T \left[ \frac{\partial n_1^T}{\partial u_1} / \|\frac{\partial f}{\partial u_1}\|, \frac{\partial n_1^T}{\partial v_1} / \|\frac{\partial f}{\partial v_1}\| \right]. \end{aligned} \quad (23)$$

We see that for the contact interaction between an IAB and the head, for a  $U \subset \mathbb{R}^2$  we must choose an appropriate  $f_i : U_i \rightarrow S_i \subset \mathbb{R}^3$  in order to characterize the setup.

### III. MULTI-IAB KINEMATICS

At a material point,  $\mathbf{r}$ , of the IAB surface in the configuration  $\mathcal{B}$ , the 3D position of a point based on the radial distance  $r$  from the origin and the angles  $\phi$  and  $\theta$  is given by (24).

$$\mathbf{R} = \begin{bmatrix} R \cos \Theta \sin \Phi \\ R \sin \Theta \sin \Phi \\ R \cos \Phi \end{bmatrix} \quad \text{and} \quad \mathbf{r} = \begin{bmatrix} r \cos \theta \sin \phi \\ r \sin \theta \sin \phi \\ r \cos \phi \end{bmatrix}. \quad (24)$$

Since deformation is radially symmetric, it follows that the regularity of the IAB in its current configuration,  $\chi(\mathbf{r}, t)$ , implies that it can be uniformly defined by  $\mathbf{r}$  throughout the IAB material body. Similar to [3], we are interested in the final state of the IAB after deformation; the path it takes for us to reach the final configuration is not important to us (since there is no obstacle in the continuum robots' workspace). Thus we drop the time dependence on the configuration and take  $\mathbf{r}$  to be the generalized coordinate of the IAB. The configuration space of the IAB with respect to the spatial frame at a certain time can then be described by  $g_{st}(\chi) \equiv g_{st}(\mathbf{r}) : \mathbf{r} \rightarrow g_{st}(\mathbf{r}) \in SE(3)$  while the strain state of the IAB is characterized by the strain field

$$\hat{\xi}_i(\mathbf{r}) = g_i^{-1} \frac{\partial g_i}{\partial \mathbf{r}} \in \mathfrak{se}(3) = g_i^{-1} g'_i \quad (25)$$

with the respective  $g'_i$ s being the tangent vector at  $g_i$  such that  $g'_i \in T_{g_i(\mathbf{r})} SE(3)$ . Note that  $T_{g_i(\mathbf{r})}$  is the tangent matrix at  $g_i$  with associated Lie algebra  $\mathfrak{se}(3) \approx T_e SE(3)$ .

#### A. End Effector Forces

From the derived relationship between the head contact coordinates and the relative motion  $(v_t, \omega_t)$  of the IAB *i.e.* equation (21), we can associate a Jacobian that maps IAB velocities to head position and orientation. A basic assumption in our formulation is that the IABs make contact with the head throughout manipulation, and the manipulation is stable and prehensile. A forward kinematic map from the configuration of the  $i$ 'th IAB,  $\chi_{iab_i}$  maps from respective IAB configurations to head position and orientation *i.e.*  $K_{iab_i} : \chi_{iab_i} \rightarrow SE(3)$ . The velocity of the head with respect to a fixed base frame in terms of IAB velocities can be written in terms of the forward kinematics Jacobian:

$$\begin{pmatrix} v_{iab_i} \\ \omega_{iab_i} \end{pmatrix} = \frac{\partial K_{iab_i}}{\partial \mathbf{r}_i} \frac{d\mathbf{r}}{dt} K_{iab_i}^{-1} = \mathbf{J}_i(\mathbf{r}_i) \dot{\mathbf{r}}_i \quad (26)$$

where  $\mathbf{r}_i$  is the spatial position of IAB  $i$ , and  $(v_{iab_i}^T, \omega_{iab_i}^T) \in \mathbb{R}^6$  represents the linear and angular velocity of the  $i^{th}$  IAB about its screw basis. In essence,  $\mathbf{r}_i \in \mathbb{R}^3$  with its rows of mapped to scalars by an appropriate choice of norm. The contact between the head and the IABs is mapped by the Jacobian

$$\mathbf{J}_{c_i}(\xi_h, \xi_{iab_i}) = \begin{bmatrix} \mathbf{I} & \hat{\mathbf{w}}(r_{c_i}) \\ \mathbf{0} & \mathbf{I} \end{bmatrix} \mathbf{J}_{r_i}, \quad (27)$$

where  $\mathbf{J}_{c_i} : \dot{\xi}_{r_i} \rightarrow [v_{c_i}^T, w_{c_i}^T]^T$ ,  $r_{c_i} \in \mathbb{R}^3$  is a vector between the head reference point (e.g. the center of mass) and the contact with the  $i^{th}$  IAB,  $\xi_h$  is the position and relative orientation of the head,  $\xi_{iab_i}$  is the position and relative orientation of the  $i^{th}$  soft robot in world coordinates,  $\hat{w}(r_{c_i})$  is an anti-symmetric matrix for the vector  $r_{c_i}$ , and  $\xi_r = (\xi_{r_1}, \xi_{r_2}, \dots, \xi_{r_8})$  are the positions and orientations for each of the 8 IABs. The manipulation map,  $G_i$  is made up of matrices of the form

$$G_i(\xi_h, \xi_r) = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \hat{w}(r_{c_i}) & \mathbf{I} \end{bmatrix} B_i(\xi_h, \xi_r), \quad (28)$$

where  $B_i(\xi_h, \xi_r)$  is the selection map as defined in [24] for the desired manipulation. The net force on the head is a sum of the individual forces arising from each IAB. Owing to the linearity of each individual IAB's contact force, the resultant head force can be stitched together to form  $G$ , i.e.

$$\tilde{F}_h = [G_1, \dots, G_8] \begin{pmatrix} \tilde{F}_{c_1} \\ \vdots \\ \tilde{F}_{c_8} \end{pmatrix} = G \tilde{F}_c, \quad (29)$$

where  $F_h \in \mathbb{R}^6$  and  $F_c \in \mathbb{R}^{m_1} \times \mathbb{R}^{m_2} \times \dots \times \mathbb{R}^{m_8}$ . The *internal* or *null forces* is captured by the null space  $\mathcal{N}(G)$  of the manipulation map  $G$ ; these forces correspond to zero net force on the head of the patient. Each  $\tilde{F}_{c_i}$  in (29) is of the form (14).

### B. End-effector Velocities

Following [23], we define the velocity constraint dual of (28) as the constraint between the relative velocity of the head and that of the twist velocities of the contact point

$$\begin{pmatrix} \tilde{v}_{c_i} \\ \tilde{\omega}_{c_i} \end{pmatrix} = \begin{bmatrix} \mathbf{I} & \hat{w}(r_{c_i}) \\ 0 & \mathbf{I} \end{bmatrix} \begin{pmatrix} v_{c_h} \\ \omega_{c_h} \end{pmatrix}. \quad (30)$$

For a conjugate twist vector  $(v_c^T, \omega_c^T)^T$  to the the forces exerted by the IABs,  $f_c$ , we have the following

$$\begin{pmatrix} v_c \\ \omega_c \end{pmatrix} = G^T \begin{pmatrix} v_{c_h} \\ \omega_{c_h} \end{pmatrix}. \quad (31)$$

Given a *selection matrix*  $B_i^T(\xi_h, \xi_{iab_i}) \in \mathbb{R}_i^m$  for a particular manipulation task, where  $m_i$  is the range of all the forces and moments for the chosen contact primitive (or union of contact primitives), the *manipulation map* for the  $i^{th}$  IAB can be written as,

$$G_i^T(\xi_h, \xi_{iab_i}) \xi_h = B_i^T(\xi_h, \xi_{iab_i}) \mathbf{J}_{c_i}(\xi_h, \mathbf{r}_{r_i}) \dot{\xi}_{iab_i} \quad (32)$$

where  $\mathbf{J}_{c_i}$  is the contact Jacobian for the  $i^{th}$  soft robot, and  $\xi_h$  denotes the velocity of the head. In the arrangement of ??, for the 8 soft robots, the manipulation constraint of the system can be written as

$$\begin{bmatrix} G_1^T \\ G_2^T \\ \vdots \\ G_8^T \end{bmatrix} \begin{pmatrix} v_h \\ w_h \end{pmatrix} = \mathbf{diag} \begin{pmatrix} B_1^T \mathbf{J}_{c_1} \\ B_2^T \mathbf{J}_{c_2} \\ \vdots \\ B_8^T \mathbf{J}_{c_8} \end{pmatrix} \begin{pmatrix} \dot{\mathbf{r}}_{iab_1} \\ \dot{\mathbf{r}}_{iab_2} \\ \vdots \\ \dot{\mathbf{r}}_{iab_8} \end{pmatrix}. \quad (33)$$

In what follows below, we give examples of the composition of the head manipulation map under different scenarios on a

treatment table. These would be helpful when we use (32) to determine the head velocity in world coordinates. In these examples, there is an implicit assumption that the angle of tilt of the head around the axis of normal is measurable by a gyroscope or a vision sensor or other sensors of similar facsimile. We show how to find the manipulation map of the head when the IAB kinematic chain underneath the head are passive, and only the four IABs surrounding the head are actuated (see ??) i.e. roll motion of the head. We then present finding the manipulation map of the head when all 8 IABs are simultaneously active i.e. the pitch, roll and yaw motion of the head.

## IV. HEAD-IAB SYSTEM'S NEWTON-EULER EQUATIONS

From the *determinism principle for stress* [25], the Cauchy stress  $\sigma$  at any point in a material at time  $t$  for any motion up to time  $t$  determines the stress response of the material for any arbitrary motion history up to and including time  $t$ . We will derive the dynamics of the IAB system in the *strain field of the deformation*. The potential and kinetic energy of the system are considered to be derived from the constitutive strain field relations that characterize the deformation. We now use Lagrangian deformation analysis to derive the dynamic equations of the continuum multi-IAB system of ??.

The constitutive law which describes the macroscopic IAB material behavior with respect to a reference frame,  $T$ , at a time,  $t$  can be completely characterized by ten dependent variables viz., three components of the position vector, six component stress tensor variables (the shear and normal stress components), and the density,  $\rho$ , of the material [21, §4.1.1].

### A. Lagrange's Equations

We are interested in the final position and orientation of the IAB as a whole rather than the system of particles that characterize a deformation at every time  $t$ . For a kinetic energy  $T$  and a potential energy  $V$ , the *Lagrangian*,  $L$ , of the system in generalized coordinates is the difference between the kinetic and potential energy, i.e.

$$L(\mathbf{r}, \dot{\mathbf{r}}) = T(\mathbf{r}, \dot{\mathbf{r}}) - V(\mathbf{r}). \quad (34)$$

The equations of motion for the pneumatic system is of the form

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\mathbf{r}}_i} - \frac{\partial L}{\partial \mathbf{r}_i} = \tau_i, \quad i = 1, \dots, m \quad (35)$$

where  $\tau_i$  is the torque acting on the  $i^{th}$  generalized coordinate. Written in matrix form equation (35) becomes

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\mathbf{r}}} - \frac{\partial L}{\partial \mathbf{r}} = \boldsymbol{\tau}. \quad (36)$$

It now remains to derive the kinetic and potential energies for the IAB material. Let the velocity of an IAB material particle  $\mathbf{x}$  in the current configuration at time  $t$  be  $\mathbf{v}(\mathbf{r}, t)$ , then the Eulerian velocity gradient tensor can be defined as

$$\boldsymbol{\Gamma} = \text{grad } \mathbf{v}(\mathbf{r}, t). \quad (37)$$

The first law of Cauchy's law of motion will allow us to derive the balance of mechanical energy of the system. Multiplying

equation (??) throughout by  $\mathbf{v}(\mathbf{r}, t)$ , and abusing notation by dropping the arguments of  $\mathbf{v}(\mathbf{r}, t)$ , we find that

$$\begin{aligned} & \text{div}(\sigma^T \cdot \mathbf{v}) + \rho \mathbf{b} \cdot \mathbf{v} = \rho \mathbf{v} \cdot \dot{\mathbf{v}} \\ \implies & \text{div}(\sigma^T \mathbf{v}) - \mathbf{tr}(\sigma \Gamma) + \rho \mathbf{b} \cdot \mathbf{v} = \rho \mathbf{v} \cdot \dot{\mathbf{v}}. \end{aligned} \quad (38)$$

Following mass conservation, we integrate over volume  $\mathcal{B}$  and employ the divergence theorem, so that the above relation yields the *balance of mechanical energy*:

$$\int_{\mathcal{B}} \rho \mathbf{b} \cdot \mathbf{v} dv + \int_{\partial \mathcal{B}} f_\rho \cdot \mathbf{v} da = \frac{d}{dt} \int_{\mathcal{B}} \frac{1}{2} \rho \mathbf{v} \cdot \mathbf{v} dv + \int_{\mathcal{B}} \mathbf{tr}(\sigma \Gamma) dv \quad (39)$$

where  $f_\rho$  is the IAB body force density, and the left hand side of the foregoing is the so-called *rate of working of the applied forces*. The symmetry of the stress tensor  $\sigma$  implies that  $\mathbf{tr}(\sigma \Gamma) = \mathbf{tr}(\sigma \Sigma)$  where  $\Sigma$  is given in terms of the Eulerian-strain rate tensor,  $\Gamma$  *i.e.*

$$\Sigma = \frac{1}{2}(\Gamma + \Gamma^T) \quad (40)$$

so that the kinetic energy density and stress power are given by,

$$T(\mathbf{r}, \dot{\mathbf{r}}) = \frac{1}{2} \rho \mathbf{v} \cdot \mathbf{v}, \quad V(\mathbf{r}) = \mathbf{tr}(\sigma \Sigma). \quad (41)$$

The stress-strain relation for the IAB we have presented are only related through the deformation tensor dependence, implying that the material is Cauchy elastic. For Cauchy elastic materials, the stress power term is not conserved during deformation making integration over the material body  $\mathcal{B}$  physically unrealistic [21]. For such materials, we may set the stored strain energy  $V$  to an arbitrary constant (e.g. an identity or  $V(I) = 0$ ). We can derive the overall torque dynamics of an IAB system as

$$\begin{aligned} \tau = & \underbrace{\begin{bmatrix} \rho & 0 & 0 \\ 0 & \rho r^2 & 0 \\ 0 & 0 & \rho r^2 \sin^2 \phi \end{bmatrix}}_{M_{iab}} \begin{bmatrix} \ddot{r} \\ \ddot{\phi} \\ \ddot{\theta} \end{bmatrix} \\ & + \underbrace{\text{diag} \begin{bmatrix} 2\rho r (\dot{\theta} \sin^2 \phi + \dot{\phi}) \\ \rho r (r \dot{\theta} \sin 2\phi - \dot{\phi}) \\ -\rho r \dot{\theta} \sin \phi (r \cos \phi + \sin \phi) \end{bmatrix}}_{C_{iab}} \begin{bmatrix} \dot{r} \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix} \end{aligned} \quad (42)$$

Rewriting equation (42) in terms of the torque for each soft robot in ??, we have the dynamics for IAB  $j$  as

$$M_{iab_j}(r_j, \phi_j) \ddot{\mathbf{r}}_j + C_{iab_j}(r_j, \phi_j, \dot{\theta}_j, \dot{\phi}_j) \dot{\mathbf{r}}_j = \boldsymbol{\tau}_j \quad (43)$$

where  $M_{iab_j}$  and  $C_{iab_j}$  are the respective inertia and Coriolis forces matrices for the soft robot,  $j$  while  $\boldsymbol{\tau}$  is the actuator torque. Since the material of the IAB is incompressible, the mass density is uniform throughout the body of the material. In general, we write equation (43) as

$$M_{iab}(\tilde{\mathbf{r}}) \ddot{\tilde{\mathbf{r}}} + C_{iab}(\tilde{\mathbf{r}}, \dot{\tilde{\mathbf{r}}}) \dot{\tilde{\mathbf{r}}} = \tilde{\boldsymbol{\tau}} \quad (44)$$

where  $\tilde{\mathbf{r}} \in \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} \times \dots \times \mathbb{R}^{n_s}$  gives the generalized coordinates for all the IABs and  $\tilde{\boldsymbol{\tau}}$  are the vectorized torques of the individual robots.

## V. NEWTON-EULER EQUATIONS

The dynamics of the head is a form of (44) but without the actuator torques. In local coordinates, it has the form

$$M_h(\zeta) \ddot{\zeta} + C_h(\zeta, \dot{\zeta}) \dot{\zeta} + N_h(\zeta, \dot{\zeta}) = 0 \quad (45)$$

with  $\zeta$  being a local parameterization of the position and orientation of the head,  $x_h \in SE(3)$ , and  $N_h$  being the gravitational and frictional forces. The head and the multi-DOF IAB system are connected via manipulation constraint *i.e.*

$$G^T(\zeta, \mathbf{r}) \dot{\zeta} = \mathbf{J}(\zeta, \mathbf{r}) \dot{\mathbf{r}}. \quad (46)$$

Suppose that the velocity constraint produces a virtual displacement constraint in  $\delta \zeta$  and  $\delta \mathbf{r}$  such that for  $q = (\zeta, \mathbf{r})$ , we have

$$\delta \mathbf{r} = \mathbf{J}^{-1}(q) G^T(q) \delta \zeta$$

the Lagrange equations become

$$\left( \frac{d}{dt} \frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q} - (\boldsymbol{\tau}, 0) \right) \delta q = 0 \quad (47)$$

$$\left( \frac{d}{dt} \frac{\partial L}{\partial \dot{\mathbf{r}}} - \frac{\partial L}{\partial \mathbf{r}} - \boldsymbol{\tau} \right)^T \begin{pmatrix} \delta \mathbf{r} \\ \delta \zeta \end{pmatrix} = 0 \quad (48)$$

$$\begin{aligned} & \left( \frac{d}{dt} \frac{\partial L}{\partial \dot{\mathbf{r}}} - \frac{\partial L}{\partial \mathbf{r}} - \boldsymbol{\tau} \right) \delta \mathbf{r} + \left( \frac{d}{dt} \frac{\partial L}{\partial \dot{\zeta}} - \frac{\partial L}{\partial \zeta} \right) \delta \zeta = 0 \\ GJ^{-T} \left( \frac{d}{dt} \frac{\partial L}{\partial \dot{\mathbf{r}}} - \frac{\partial L}{\partial \mathbf{r}} - \boldsymbol{\tau} \right) \delta \zeta + \left( \frac{d}{dt} \frac{\partial L}{\partial \dot{\zeta}} - \frac{\partial L}{\partial \zeta} \right) \delta \zeta = 0 \end{aligned} \quad (49)$$

from where

$$\left( \frac{d}{dt} \frac{\partial L}{\partial \dot{\zeta}} - \frac{\partial L}{\partial \zeta} \right) \delta \zeta + GJ^{-T} \left( \frac{d}{dt} \frac{\partial L}{\partial \dot{\mathbf{r}}} - \frac{\partial L}{\partial \mathbf{r}} \right) = GJ^{-T} \boldsymbol{\tau} \quad (50)$$

given the arbitrariness of  $\delta \zeta$ . Equations (50) alongside (46) completely describe the system.

## VI. MANIPULATION EXAMPLES

### A. Case I: Planar and Roll Manipulation

Consider a planar manipulation of the head as shown in Figure 4. Again, we use the cone of forces to model a *point contact* [17] between the head and soft robots. In this case, the robots beneath the head are passive while the side robots are actuated. For each IAB, the orientation of the vector  $r_{c_i}$  with respect to the vertical, measured counterclockwise is  $\phi_i$  when the head lies on the  $xy$  plane; the manipulation matrix maps IAB forces into  $x$  and  $y$  forces as well as a torque perpendicular to the  $xy$  plane. We have the manipulation map as

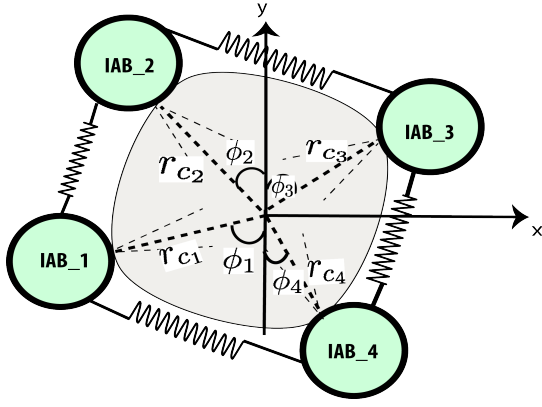


Fig. 4. Planar head manipulation with net force on the head.

$$\begin{aligned}
 G_1 &= \begin{bmatrix} \mathbf{I} & 0 \\ \begin{pmatrix} -r_{c1} \sin \phi_1 \\ -r_{c1} \cos \phi_1 \\ 0 \end{pmatrix} & \mathbf{I} \end{bmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}, \\
 G_2 &= \begin{bmatrix} \mathbf{I} & 0 \\ \begin{pmatrix} -r_{c2} \sin \phi_2 \\ r_{c2} \cos \phi_2 \\ 0 \end{pmatrix} & \mathbf{I} \end{bmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}, \\
 G_3 &= \begin{bmatrix} \mathbf{I} & 0 \\ \begin{pmatrix} r_{c3} \sin \phi_3 \\ r_{c3} \cos \phi_3 \\ 0 \end{pmatrix} & \mathbf{I} \end{bmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}, \\
 G_4 &= \begin{bmatrix} \mathbf{I} & 0 \\ \begin{pmatrix} r_{c4} \sin \phi_4 \\ -r_{c4} \cos \phi_4 \\ 0 \end{pmatrix} & \mathbf{I} \end{bmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \quad (51)
 \end{aligned}$$

whereupon, the planar manipulation map for the head becomes

$$G(x, y, \phi) = \begin{bmatrix} 1 & 0 & r_{c1} \cos \phi_1 \\ 0 & 1 & -r_{c1} \sin \phi_1 \\ 1 & 0 & -r_{c2} \cos \phi_2 \\ 0 & 1 & -r_{c2} \sin \phi_2 \\ 1 & 0 & -r_{c3} \cos \phi_3 \\ 0 & 1 & r_{c3} \sin \phi_3 \\ 1 & 0 & r_{c4} \cos \phi_4 \\ 0 & 1 & r_{c4} \sin \phi_4 \end{bmatrix}^T \quad (52)$$

for all forces with respect to the  $xy$  coordinates shown in Figure 4.

### B. Case II: Planar Manipulation: Null Map for Zero Net Force

Now consider the case where all the vectors between each IAB in the  $xy$  plane and the head have equal magnitude such that the angle made by the head with respect to the vertical axis ( $y$ ) is  $\phi$  (see Figure 5). The head rolls around the vertical by an angle  $\phi$  as shown. It follows that the manipulation map

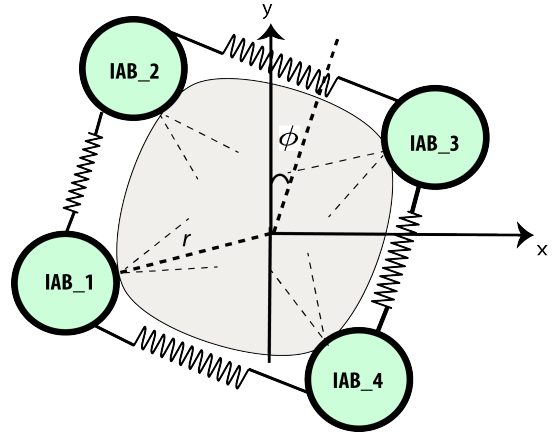


Fig. 5. Planar head manipulation with no net force on the head. [Image best visualized in colored ink].

is

$$G_i(x, y, \phi) = \begin{bmatrix} \mathbf{I} & 0 \\ \begin{pmatrix} \pm r \sin \phi \\ \pm r \cos \phi \\ 0 \end{pmatrix} & \mathbf{I} \end{bmatrix} \begin{pmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \quad (53)$$

so that

$$G(x, y, \phi) = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ r \cos \phi & -r \sin \phi & -r \cos \phi & -r \sin \phi & -r \cos \phi & r \sin \phi \end{bmatrix} \quad (54)$$

where again all forces are measured with respect to the  $xy$  plane of Figure 5. The IAB's  $x$  and  $y$  forces result in an equal  $x$  and  $y$  forces on the head; the overall torque is proportional to the head orientation. When forces are applied along the line connecting diagonally oriented IABs (e.g. the lines connecting IAB<sub>1</sub> and IAB<sub>3</sub>), there will be no net force on the head as the null space of the map becomes spanned by the vector

$$\begin{pmatrix} 0 & 0 & -\frac{\sin \phi}{\cos \phi} & -r & -\frac{\sin \phi}{\cos \phi} \\ -r & 0 & -r & 0 & -r \\ 0 & -r & \frac{\sin \phi}{\cos \phi} & 0 & -\frac{\sin \phi}{\cos \phi} \\ r & 0 & 0 & 0 & 0 \\ 0 & r & 0 & 0 & 0 \\ 0 & 0 & r & 0 & 0 \\ 0 & 0 & 0 & r & 0 \\ 0 & 0 & 0 & 0 & r \end{pmatrix}. \quad (55)$$

### C. Case III: Head Motion along $xy$ plane and $z$

Consider the case where all 8 soft robots are actuated such that the head is raised to a height,  $h$ , on the treatment machine, and it is tilted along the  $xy$  plane as shown in left figure of Figure 6. Suppose the orientation of the head is by an angle  $\phi$  as in Figure 5. We now describe the manipulation map for the IAB-head system.

$$G_i(x, y, \phi) = \begin{bmatrix} \mathbf{I} & 0 \\ \begin{pmatrix} \pm r \sin \phi \\ \pm r \cos \phi \\ h \end{pmatrix} & \mathbf{I} \end{bmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (56)$$



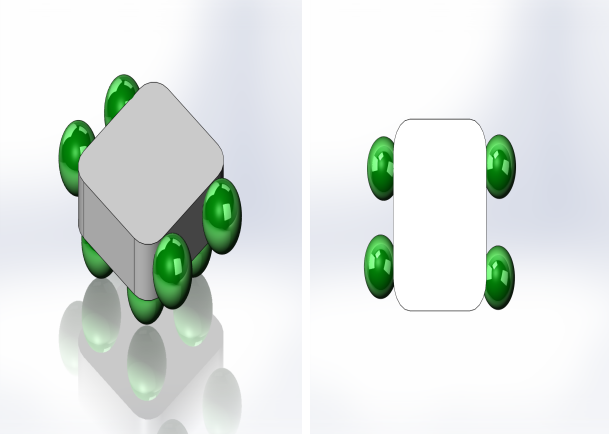


Fig. 6. Head manipulation with all eight bladders. Head depicted with the silver-colored geometric primitive. [Image best visualized in colored ink].

so that

$$G(x, y, \phi) = \begin{pmatrix} 1 & 0 & r \cos \phi \\ 0 & 1 & -r \sin \phi \\ 1 & 0 & -r \cos \phi \\ 0 & 1 & r \sin \phi \\ 1 & 0 & -r \cos \phi \\ 0 & 1 & r \sin \phi \\ 1 & 0 & r \cos \phi \\ 0 & 1 & r \sin \phi \end{pmatrix} \quad (57)$$

## VII. CONCLUSIONS

We have presented the kinematic motion equations and the Lagrangian dynamics for the mechanism presented in our previous publication. It remains to demonstrate the working examples in closed-loop head motion control. In a follow-up paper to be released shortly, we show how these formulations are applied in real-time on the patient-IAB system.

### APPENDIX A IAB DYNAMICS

We now derive the overall dynamics for the elastic IAB in Eulerian form. Following (24), a point on the surface of the IAB has the following Cartesian description

$$\begin{aligned} \mathbf{r} &= \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} r \cos \theta \sin \phi \\ r \sin \theta \sin \phi \\ r \cos \phi \end{bmatrix} \\ \dot{\mathbf{r}} &= \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} \dot{r} \cos \theta \sin \phi - r \dot{\theta} \sin \theta \sin \phi + r \dot{\phi} \cos \theta \cos \phi \\ \dot{r} \sin \theta \sin \phi + r \dot{\theta} \cos \theta \sin \phi + r \dot{\phi} \sin \theta \cos \phi \\ \dot{r} \cos \phi - r \dot{\phi} \sin \phi \end{bmatrix} \end{aligned} \quad (58)$$

and since the deformation is radially symmetric, we expect that  $\mathbf{r}$  has a uniform value throughout the IAB boundary. We

find that the components of  $\ddot{\mathbf{r}}$  are

$$\begin{aligned} \ddot{x} &= \cos \theta \left( 2\dot{r}\dot{\phi} \cos \theta + r \cos \theta \ddot{\phi} - 2r\dot{\theta}\dot{\phi} \sin \theta \right) \\ &\quad - \sin \phi \left( \cos \theta \left( -\ddot{r} + r\dot{\theta}^2 + r\dot{\phi}^2 \right) + \sin \theta \left( 2\dot{r}\dot{\theta} + r\ddot{\theta} \right) \right) \\ \ddot{y} &= \cos \phi \left( 2r\dot{\theta}\dot{\phi} \cos \theta + \left( 2\dot{r}\dot{\phi} + r\ddot{\phi} \right) \sin \theta \right) \\ &\quad + \sin \phi \left( 2\dot{r}\dot{\theta} \cos \theta + r\ddot{\theta} \cos \theta + \sin \theta \left( \ddot{r} - r\dot{\theta}^2 - r\dot{\phi}^2 \right) \right) \\ \ddot{z} &= \cos \phi \left( \ddot{r} - r\dot{\phi}^2 \right) - \sin \phi \left( 2\dot{r}\dot{\phi} + r\ddot{\phi} \right). \end{aligned} \quad (59)$$

Recall the kinetic energy form of a continuum body (§ IV)

$$T = \frac{1}{2} \rho \mathbf{v}(\mathbf{r}, t) \cdot \mathbf{v}(\mathbf{r}, t) = \frac{1}{2} \rho \|\dot{\mathbf{r}}\|^2. \quad (60)$$

The constitutive equation that governs the Cauchy stress tensor,  $\boldsymbol{\sigma}$  is independent of the path of the deformation from the reference configuration and it is solely a function of the state of deformation; in other words, this is a Cauchy elastic material. We therefore choose  $V = 0$  following [21]'s recommendation. Since we are treating an incompressible material, the material mass density is uniform throughout the body in its configuration. Thus the rate of change of  $\rho$  vanishes. We therefore have

$$T = \frac{1}{2} \rho \|\dot{\mathbf{r}}\|^2 = \frac{1}{2} \rho \left( \dot{r}^2 + r^2 \dot{\phi}^2 + r^2 \dot{\theta}^2 \sin^2 \phi \right), \quad V = 0. \quad (61)$$

It follows that the Lagrangian is

$$L(\mathbf{r}, \dot{\mathbf{r}}) = \frac{1}{2} \rho \left( \dot{r}^2 + r^2 \dot{\phi}^2 + r^2 \dot{\theta}^2 \sin^2 \phi \right). \quad (62)$$

and the derivatives of the canonical momenta are

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{r}} = \frac{d}{dt} (\rho \dot{r}) = \rho \ddot{r} \quad (63a)$$

$$\begin{aligned} \frac{d}{dt} \frac{\partial L}{\partial \dot{\theta}} &= \frac{d}{dt} \left( r^2 \rho \dot{\theta} \sin^2 \phi \right) = 2\rho r \dot{r} \dot{\theta} \sin^2 \phi \\ &\quad + 2\rho r^2 \dot{\phi} \dot{\theta} \sin \phi \cos \phi + \rho r^2 \ddot{\theta} \sin^2 \phi \end{aligned} \quad (63b)$$

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\phi}} = \frac{d}{dt} \left( r^2 \rho \dot{\phi} \right) = 2\rho \dot{r} r \dot{\phi} + \rho r^2 \ddot{\phi} \quad (63c)$$

with the following associated generalized forces

$$\begin{aligned} \frac{\partial L}{\partial r} &= \rho r \dot{\phi}^2 + \rho r \dot{\theta}^2 \sin^2 \phi, \quad \frac{\partial L}{\partial \theta} = 0, \\ \frac{\partial L}{\partial \phi} &= \rho r^2 \dot{\theta}^2 \cos \phi \sin \phi. \end{aligned} \quad (64a)$$

So that we may write the general system dynamics as

$$\begin{aligned} \boldsymbol{\tau} &= \rho \left\{ \ddot{r} + r \left[ r \ddot{\phi} + 2\dot{r} \left( \dot{\phi} + \dot{\theta} \sin^2 \phi \right) \right. \right. \\ &\quad \left. \left. + \sin \phi \left( r \ddot{\theta} \sin \phi - \dot{\theta}^2 (r \cos \phi + \sin \phi) \right) \right. \right. \\ &\quad \left. \left. + \dot{\phi} \left( -\dot{\phi} + r \dot{\theta} \sin 2\phi \right) \right] \right\} \end{aligned} \quad (65)$$

or in matrix form

$$\begin{aligned} \tau = & \begin{bmatrix} \rho & 0 & 0 \\ 0 & \rho r^2 & 0 \\ 0 & 0 & \rho r^2 \sin^2 \phi \end{bmatrix} \begin{bmatrix} \ddot{r} \\ \ddot{\phi} \\ \ddot{\theta} \end{bmatrix} \\ & + \text{diag} \begin{bmatrix} 2\rho r (\dot{\theta} \sin^2 \phi + \dot{\phi}) \\ \rho r (r\dot{\theta} \sin 2\phi - \dot{\phi}) \\ -\rho r \dot{\theta} \sin \phi (r \cos \phi + \sin \phi) \end{bmatrix} \begin{bmatrix} \dot{r} \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix}. \end{aligned} \quad (66)$$

## APPENDIX B

### DERIVATION OF IAB-HEAD CONTACT KINEMATICS

Here, we formulate the contact kinematics between an IAB and the head in a fashion similar to the single finger soft contact type postulated in [23]. We note that an alternative derivation that is more concise can be found in [18].

#### A. Contact Coordinates and Gaussian Map

Following equations (16a), (16b), and 17, we write

$$R f_1(\alpha_1) + p = f_h(\alpha_h) \quad (67a)$$

$$R n_1(\alpha_1) = -n_h(\alpha_h) \quad (67b)$$

$$R \frac{\partial f_1}{\partial \alpha_1} M_1^{-1} R_\psi = \frac{\partial f_h}{\partial \alpha_h} M_h^{-1}. \quad (67c)$$

Differentiating (67a) and (67b), we find that

$$\dot{R} f_1(\alpha_1) + R \frac{\partial f_1}{\partial \alpha_1} \dot{\alpha}_1 + \dot{p} = \frac{\partial f_h}{\partial \alpha_h} \dot{\alpha}_h \quad (68)$$

$$\dot{R} n_1(\alpha_1) + R \frac{\partial n_1}{\partial \alpha_1} \dot{\alpha}_1 = -\frac{\partial n_h}{\partial \alpha_h} \dot{\alpha}_h. \quad (69)$$

It follows through the multiplication of (68) by  $\frac{\partial f_h}{\partial \alpha_h}^T$  and putting  $\alpha_h$  into (69), we have

$$\begin{aligned} \dot{R} n_1(\alpha_1) + R \frac{\partial n_1}{\partial \alpha_1} \dot{\alpha}_1 = & -\frac{\partial n_h}{\partial \alpha_h} M_h^{-2} \frac{\partial f_h}{\partial \alpha_h}^T \\ & \left( \dot{R} f_1(\alpha_1) + R \frac{\partial f_1}{\partial \alpha_1} \dot{\alpha}_1 + \dot{p} \right). \end{aligned} \quad (70)$$

Now, putting (67c) into (70) and rearranging, we find that

$$\begin{aligned} & \left[ R \frac{\partial n_1}{\partial \alpha_1} + \frac{\partial n_h}{\partial \alpha_h} M_h^{-2} \left( \frac{\partial f_h^T}{\partial \alpha_h} \frac{\partial f_h}{\partial \alpha_h} \right) M_h^{-1} R_\psi M_1 \right] \dot{\alpha}_1 \\ & = -\dot{R} n_1 - \frac{\partial n_h}{\partial \alpha_h} M_h^{-2} \frac{\partial f_h}{\partial \alpha_h}^T \left( \dot{R} f_1(\alpha_1) + \dot{p} \right). \end{aligned} \quad (71)$$

Multiplying throughout by  $M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T$ , we have on the left hand side of the above as,

$$M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T \left( R \frac{\partial n_1}{\partial \alpha_1} + \frac{\partial n_h}{\partial \alpha_h} M_h^{-1} R_\psi M_1 \right) \dot{\alpha}_1. \quad (72)$$

Since

$$\begin{aligned} M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T &= \frac{\partial f_h}{\partial \alpha_h} M_h^{-1} = \left( R \frac{\partial f_1}{\partial \alpha_1} M_1^{-1} R_\psi \right)^T \\ &= R_\psi M_1^{-T} \frac{\partial f_1}{\partial \alpha_1}^T R^T, \end{aligned} \quad (73)$$

equation (72) becomes

$$\begin{aligned} \dot{\alpha}_1 & \left( R_\psi M_1^{-T} \frac{\partial f_1}{\partial \alpha_1}^T \frac{\partial n_1}{\partial \alpha_1} + M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T \frac{\partial n_h}{\partial \alpha_h} M_h^{-1} R_\psi M_1 \right) \\ &= \left( R_\psi M_1^{-T} \frac{\partial f_1}{\partial \alpha_1}^T \frac{\partial n_1}{\partial \alpha_1} M_1^{-1} R_\psi + M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T \frac{\partial n_h}{\partial \alpha_h} M_h^{-1} \right) \\ & \quad \times R_\psi M_1 \dot{\alpha}_1. \end{aligned} \quad (74)$$

Setting

$$\tilde{\mathcal{K}}_1 = R_\psi M_1^{-T} \frac{\partial f_1}{\partial \alpha_1}^T \frac{\partial n_1}{\partial \alpha_1} M_1^{-1} R_\psi$$

and

$$\mathcal{K}_h = M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T \frac{\partial n_h}{\partial \alpha_h} M_h^{-1},$$

it follows from (70) that

$$\begin{aligned} & (\tilde{\mathcal{K}}_1 + \mathcal{K}_h) R_\psi M_1 \dot{\alpha}_1 = \\ & M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T \left[ -\dot{R} n_1 - \frac{\partial n_h}{\partial \alpha_h} M_h^{-2} \frac{\partial f_h}{\partial \alpha_h}^T (\dot{R} f_1 + \dot{p}) \right] \\ & = -M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T \dot{R} n_1 - \mathcal{K}_h M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T (\dot{R} f_1 + \dot{p}) \end{aligned} \quad (75)$$

so that

$$\begin{aligned} \dot{\alpha}_1 &= (\tilde{\mathcal{K}}_1 + \mathcal{K}_h)^{-1} R_\psi M_1^{-1} \times \\ & \left[ \underbrace{-M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T \dot{R} n_1}_{w_t} - \underbrace{\mathcal{K}_h M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T (\dot{R} f_1 + \dot{p})}_{v_t} \right] \end{aligned} \quad (76)$$

or

$$\dot{\alpha}_1 = (\tilde{\mathcal{K}}_1 + \mathcal{K}_h)^{-1} R_\psi M_1^{-1} (w_t - \mathcal{K}_h v_t). \quad (77)$$

Finding the generalized velocity of the head with respect to a single IAB deformation is tantamount to finding  $(\dot{w}, v) = \dot{g} g^{-1}$ . Thus,

$$\omega_t = -M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T (\omega \times (R n_1)) = -M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T (n_h \times \omega) \quad (78)$$

$$v_t = M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T (\omega \times (R f_1) + \omega \times p + v) \quad (79)$$

$$= M_h^{-T} \frac{\partial f_h}{\partial \alpha_h}^T (-f_h \times \omega + v), \quad (80)$$

where  $\omega_t$  is the head's rolling velocity projected onto the contact's tangent plane. The rotation normal to the surface is canceled by the cross product of  $\omega$  and  $n_h$ . In the same vein,  $v_t$  is the sliding velocity between the contacts, projected onto the tangent plane. Following the above construction, we find the kinematics of the contact point of the head in local coordinates is

$$\dot{\alpha}_h = M_h^{-1} (\tilde{\mathcal{K}}_1 + \mathcal{K}_h)^{-1} (\omega_t - \tilde{\mathcal{K}}_1 v_t), \quad (81)$$

where  $(\tilde{\mathcal{K}}_1 + \mathcal{K}_h)$  is the *relative curvature* [18]. It remains to solve for the relative orientation between the two local coordinates,  $\psi$ .

### B. Relative Contact Orientation and Torsion Metric Tensors

In matrix form, (67b) and (67c) can be written as,

$$R \begin{bmatrix} \frac{\partial f_1}{\partial \alpha_1} M_1^{-1} & n_1(\alpha_1) \end{bmatrix} \begin{bmatrix} R_\psi & 0 \\ 0 & -1 \end{bmatrix} = \begin{bmatrix} \frac{\partial f_h}{\partial \alpha_h} M_h^{-1} & n_h(\alpha_h) \end{bmatrix}. \quad (82)$$

Following the normalized Gaussian frame defined in (20), we can rewrite the above equation as

$$R[x_1 \ y_1 \ z_1] \bar{R}_\psi = [x_h \ y_h \ z_h]. \quad (83)$$

The total derivative of (83) yields

$$\begin{aligned} \dot{R} \begin{bmatrix} x_1 & y_1 & z_1 \end{bmatrix} \bar{R}_\psi + R \begin{bmatrix} \dot{x}_1 & \dot{y}_1 & \dot{z}_1 \end{bmatrix} \bar{R}_\psi + \\ R \begin{bmatrix} x_1 & y_1 & z_1 \end{bmatrix} \begin{bmatrix} \dot{R}_\psi & 0 \\ 0 & 0 \end{bmatrix} &= \begin{bmatrix} \dot{x}_h \\ \dot{y}_h \\ \dot{z}_h \end{bmatrix}^T. \end{aligned} \quad (84)$$

Premultiplying by  $y_1^T R^T$  and then postmultiplying by  $\bar{R}_\psi \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$ , with the knowledge that  $\bar{R}_\psi \bar{R}_\psi = \mathbf{I}$ , and the identity  $y_1^T y_1 = 1$ , we find that

$$\begin{aligned} y_1^T R^T \dot{R} \begin{bmatrix} x_1 & y_1 & z_1 \end{bmatrix} \bar{R}_\psi + y_1^T \begin{bmatrix} \dot{x}_1 & \dot{y}_1 & \dot{z}_1 \end{bmatrix} \bar{R}_\psi \\ + (0 \ 1 \ 0) \begin{bmatrix} \dot{R}_\psi & 0 \\ 0 & 0 \end{bmatrix} &= y_1^T R^T \begin{bmatrix} \dot{x}_h & \dot{y}_h & \dot{z}_h \end{bmatrix} \end{aligned} \quad (85)$$

$$\begin{aligned} y_1^T R^T \dot{R} x_1 + y_1^T \dot{x}_1 + (0 \ 1 \ 0) \begin{bmatrix} \dot{R}_\psi R_\psi & 0 \\ 0 & 0 \end{bmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \\ = y_1^T R^T \begin{bmatrix} \dot{x}_h & \dot{y}_h & \dot{z}_h \end{bmatrix} \bar{R}_\psi \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \end{aligned} \quad (86)$$

$$\begin{aligned} y_1^T R^T \dot{R} x_1 + y_1^T \dot{x}_1 + (0 \ 1) \begin{bmatrix} 0 & \dot{\psi} \\ -\dot{\psi} & 0 \end{bmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\ = y_1^T R^T \begin{bmatrix} \dot{x}_h & \dot{y}_h & \dot{z}_h \end{bmatrix} \bar{R}_\psi \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \end{aligned} \quad (87)$$

$$y_1^T R^T \dot{R} x_1 + y_1^T \dot{x}_1 - \dot{\psi} = y_1^T R^T \begin{bmatrix} \dot{x}_h & \dot{y}_h & \dot{z}_h \end{bmatrix} \bar{R}_\psi \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}. \quad (88)$$

From (83), we have that

$$\bar{R}_\psi^T \begin{bmatrix} x_1^T & y_1^T & z_1^T \end{bmatrix} R^T = \begin{bmatrix} x_h^T & y_h^T & z_h^T \end{bmatrix} \quad (89)$$

so that

$$\begin{bmatrix} x_1^T & y_1^T & z_1^T \end{bmatrix} R^T = \bar{R}_\psi \begin{bmatrix} x_h^T & y_h^T & z_h^T \end{bmatrix} \quad (90)$$

or

$$\begin{aligned} y_1^T R^T &= (0 \ 1 \ 0) \bar{R}_\psi \begin{bmatrix} x_h^T & y_h^T & z_h^T \end{bmatrix} \\ &= (0 \ 1) R_\psi \begin{pmatrix} x_h^T \\ y_h^T \end{pmatrix}. \end{aligned} \quad (91)$$

It follows from (88) that

$$\begin{aligned} \dot{\psi} &= y_1^T R^T \dot{R} x_1 + y_1^T \frac{\partial x_1}{\partial \alpha_1} \dot{\alpha}_1 \\ &- (0, 1) R_\psi \begin{bmatrix} x_h^T \dot{x}_h & x_h^T \dot{y}_h \\ y_h^T \dot{x}_h & y_h^T \dot{y}_h \end{bmatrix} R_\psi \begin{pmatrix} 1 \\ 0 \end{pmatrix}. \end{aligned} \quad (92)$$

Using the identities,

$$x_i^T y_i = 0, \implies \dot{x}_i^T y_i = -x_i^T \dot{y}_i = y_i^T \dot{x}_i \quad (93)$$

$$x_i^T x_i = 1, \implies \dot{x}_i^T x_i = 0, \quad (94)$$

we can rewrite (92) as

$$\begin{aligned} \dot{\psi} &= y_1^T R^T \dot{R} x_1 + y_h^T \frac{\partial x_h}{\partial \alpha_h} \dot{\alpha}_h + y_1^T \frac{\partial x_1}{\partial \alpha_1} \dot{\alpha}_1 \\ &= \omega_n + T_h M_h \dot{\alpha}_h + T_1 M_1 \dot{\alpha}_1 \end{aligned} \quad (95)$$

where

$$\begin{aligned} \omega_n &= y_1^T R^T \dot{R} x_1 = (R y_1)^T w \times (R x_1) \\ &= (R z_1)^T \omega = z_h^T \omega \end{aligned} \quad (96)$$

$$T_h = y_h^T \frac{\partial x_h^T}{\partial \alpha_h} M_h^{-T}, \quad T_1 = y_1^T \frac{\partial x_1^T}{\partial \alpha_1} M_1^{-T}. \quad (97)$$

It follows that the first, second and third equations of contact are given by (77), (81), and (95) respectively, *i.e.*

#### Equations of Contact

$$\dot{\alpha}_1 = (\tilde{\mathcal{K}}_1 + \mathcal{K}_h)^{-1} R_\psi M_1^{-1} (\omega_t - \mathcal{K}_h v_t) \quad (98a)$$

$$\dot{\alpha}_h = M_h^{-1} (\tilde{\mathcal{K}}_1 + \mathcal{K}_h)^{-1} (\omega_t - \tilde{\mathcal{K}}_1 v_t) \quad (98b)$$

$$\dot{\psi} = \omega_n + T_h M_h \dot{\alpha}_h + T_1 M_1 \dot{\alpha}_1. \quad (98c)$$

### APPENDIX C

#### CONTACT-BASED BOUNDARY VALUE PROBLEM

With the spherically symmetric deformation property, we expect that the shear stress contributions  $\sigma_{r\phi}, \sigma_{r\theta}, \sigma_{\phi\theta}$  vanish in the body forces equation so that we have from the equation of balance of linear momentum,

$$\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \sigma_{rr}) - \frac{1}{r} (\sigma_{\theta\theta} + \sigma_{\phi\phi}) + \rho b_r = \rho \ddot{r}_x \quad (99a)$$

$$\frac{1}{r \sin \phi} \frac{\partial}{\partial \phi} (\sin \phi \sigma_{\phi\phi}) - \frac{\cot \phi}{r} (\sigma_{\theta\theta}) + \rho b_\phi = \rho \ddot{r}_y \quad (99b)$$

$$\frac{1}{r \sin \phi} \frac{\partial}{\partial \theta} (\sigma_{\theta\theta}) + \rho b_\theta = \rho \ddot{r}_z \quad (99c)$$

where the mass density  $\rho$  is uniform throughout the body and the components  $\ddot{r}_x, \ddot{r}_y$ , and  $\ddot{r}_z$  are as given in (63). Solving the equations in (99), we have from (99a),

$$\begin{aligned} \frac{\partial \sigma_{rr}}{\partial r} &= \rho \ddot{r}_x + \frac{1}{r} (\sigma_{\theta\theta} + \sigma_{\phi\phi}) - \rho b_r \\ &= \frac{1}{r} (\sigma_{\theta\theta} + \sigma_{\phi\phi}) - \rho b_r \\ &+ \rho \cos \theta \left( 2\dot{r} \dot{\phi} \cos \theta + r \cos \theta \ddot{\phi} - 2r \dot{\theta} \dot{\phi} \sin \theta \right) \\ &- \rho \sin \theta \left( \cos \theta (-\ddot{r} + r \dot{\theta}^2 + r \dot{\phi}^2) + \sin \theta (2\dot{r} \dot{\theta} + r \ddot{\theta}) \right) \end{aligned} \quad (100)$$

and from (99b), we have

$$\rho \ddot{\mathbf{r}}_y = \frac{\cot \phi}{r} (\sigma_{\phi\phi} - \sigma_{\theta\theta}) + \rho b_\phi + \frac{1}{r} \frac{\partial \sigma_{\phi\phi}}{\partial \phi}$$

$$\frac{\partial \sigma_{\phi\phi}}{\partial \phi} = r \rho \ddot{\mathbf{r}}_y - r \rho b_\phi.$$

so that

$$\frac{\partial \sigma_{\phi\phi}}{\partial \phi} = -\rho r b_\theta + r \rho \left[ \cos \phi \left( 2r\dot{\theta}\dot{\phi} \cos \theta + (2\dot{r}\dot{\phi} + r\ddot{\phi}) \sin \theta \right) \right. \\ \left. + \sin \theta \left( 2\dot{r}\dot{\theta} \cos \theta + r\ddot{\theta} \cos \theta + (\ddot{r} - r\dot{\theta}^2 - r\dot{\phi}^2) \right) \sin \phi \right] \quad (101)$$

and lastly, we have from (99c)

$$\frac{\partial \sigma_{\theta\theta}}{\partial \theta} = (\rho \ddot{\mathbf{r}}_z - \rho b_\theta) r \sin \phi$$

$$= -r \rho b_\theta \sin \phi + r \rho \sin \phi \cos \phi \left( \ddot{r} - r\dot{\phi}^2 \right) \\ - r \rho \sin^2 \phi \left( 2\dot{r}\dot{\phi} + r\ddot{\phi} \right). \quad (102)$$

Collecting  $\frac{\partial \sigma_{rr}}{\partial r}$ ,  $\frac{\partial \sigma_{\theta\theta}}{\partial \theta}$ , and  $\frac{\partial \sigma_{\phi\phi}}{\partial \phi}$  above, taking  $\sigma_{rr}(r_o) = \sigma_{\theta\theta}(2\pi) = \sigma_{\phi\phi}(\pi) = 0$  and integrating from the internal to outer boundary conditions given by

$$\sigma_{rr}|_{R=R_o} = -P_{\text{atm}}, \quad \sigma_{rr}|_{R=R_i} = -P_{\text{atm}} - P \quad (103)$$

we have the full form of the normal stress components as

$$\sigma_{rr}(\delta) = - \int_{\delta}^{r_o} \left[ \frac{1}{r} \left( -2p + 2C_1 \frac{r^2}{R^2} - 2C_2 \frac{R^8}{r^8} \right) - \rho b_r \right. \\ \left. + \rho \cos \theta \left( 2\dot{r}\dot{\phi} \cos \theta + r \cos \theta \ddot{\phi} - 2r\dot{\theta}\dot{\phi} \sin \theta \right) \right. \\ \left. - \rho \sin \phi \left( \cos \theta (-\ddot{r} + r\dot{\theta}^2 + r\dot{\phi}^2) + \sin \theta (2\dot{r}\dot{\theta} + r\ddot{\theta}) \right) \right] dr \quad (104)$$

$$\sigma_{\phi\phi}(\epsilon) = - \int_{\epsilon}^{\pi} \left[ r \rho \left[ \cos \phi \left( 2r\dot{\theta}\dot{\phi} \cos \theta + (2\dot{r}\dot{\phi} + r\ddot{\phi}) \sin \theta \right) \right. \right. \\ \left. \left. \sin \theta \sin \phi \left( 2\dot{r}\dot{\theta} \cos \theta + r\ddot{\theta} \cos \theta + (\ddot{r} - r\dot{\theta}^2 - r\dot{\phi}^2) \right) \right] \right. \\ \left. - \rho r b_\theta \right] d\phi$$

$$\sigma_{\theta\theta}(\zeta) = - \int_{\zeta}^{2\pi} \left[ -r \rho b_\theta \sin \phi + r \rho \sin \phi \cos \phi \left( \ddot{r} - r\dot{\phi}^2 \right) \right. \\ \left. - r \rho \sin^2 \phi \left( 2\dot{r}\dot{\phi} + r\ddot{\phi} \right) \right] d\theta \quad (105)$$

where  $r_i \leq \delta \leq r_o$ ,  $0 \leq \epsilon \leq \pi$  and  $0 \leq \zeta \leq 2\pi$ . Now, using the boundary condition,  $P + P_{\text{atm}} = -\sigma_{rr}|_{r=r_i}$ , where  $P_{\text{atm}}$  is the atmospheric pressure, (here, taken as 0), we have the internal pressure in the IAB cavity as a function of the radius of deformation in the current configuration as

$$P = \int_{r_i}^{r_o} \left[ \frac{1}{r} \left( -2p + 2C_1 \frac{r^2}{R^2} - 2C_2 \frac{R^8}{r^8} \right) - \rho b_r \right. \\ \left. + \rho \cos \theta \left( 2\dot{r}\dot{\phi} \cos \theta + r \cos \theta \ddot{\phi} - 2r\dot{\theta}\dot{\phi} \sin \theta \right) \right. \\ \left. - \rho \sin \phi \left( \cos \theta (-\ddot{r} + r\dot{\theta}^2 + r\dot{\phi}^2) + \sin \theta (2\dot{r}\dot{\theta} + r\ddot{\theta}) \right) \right] dr. \quad (106)$$

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