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Differential geometric structures of stable state feedback systems with dual connections

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This paper gives new approach to investigate differential geometric structures of stable and stable state feedback systems. For this purpose pairs of dual connections are introduced. Some of these connections are found to characterize the geometric structures of stable state feedback systems well.

1. INTRODUCTION

There have been many differential geometric approaches to investigate structures of linear (dynamical) systems (e.g. [1]–[3]). However, it seems that differential geometric structures of feedback systems, which are very important in the engineering sense, have not been deeply studied yet.

As is widely known, the parametrization of stabilizing controllers by Youla et al. [4] and Kučera [5] has given great advantage to the control theory and its applications. Since designers of controllers must optimize various performance indices on the parametrized set of stabilizing controllers, studying its geometric structures gives useful insights.

Recently, it has been shown that the set of stable matrices and the set of stabilizing state feedback gains are diffeomorphic to some kind of vector bundles, and the set of state feedback system matrices is parametrically imbedded as a submanifold of this vector bundle [6].

In this paper, we define metrics and connections on these vector bundles to analyze the differential geometric structures of stable state feedback systems. The main tool used here is the theory of dual connections, what is called Information Geometry, extensively studied by Amari [8] in statistics. Using this theory, we can reveal the simple structures of the set of stable systems and stabilizing state feedback gains, which can not be elucidated by usual Riemannian geometry.

1 Presented at the IFAC Workshop on System Structure and Control held in Prague on September 3–5, 1992.
In this paper, \( PD(n) \), \( \text{Skew}(n) \) and \( S(n) \) denote, respectively, the set of \( n \) positive definite real matrices, skew symmetric real matrices \( (M = -M^T) \) and stable real matrices (all the eigenvalues are located in the open left half complex plane).

2. PARAMETRIZATION OF STABILIZING STATE FEEDBACK GAINS AND STABLE MATRICES

This section will give parametrizations of stabilizing state feedback gains and stable matrices using Lyapunov equations. Complete derivations of the results in this section can be found in [6].

Consider an \( n \)-dimensional linear system with \( m \) inputs represented by a state space equation:

\[
\dot{x} = Ax + Bu,
\]

where \((A, B)\) is stabilizable and \( B \) is of column full rank.

Let \( \mathcal{F}_S(A, B) \) denote the set of stabilizing state feedback gains \( F \), i.e., \( \mathcal{F}_S(A, B) := \{ F | A + BF \in S(n) \} \).

Definition.
1. Let \( Q \) be in \( PD(n) \). The set of positive definite matrices \( P \) that satisfy the following equation:

\[
(I - BB^\dagger)(AP + PA^T + Q)(I - BB^\dagger) = 0
\]

is denoted by \( PD(n; A, B, Q) \).

2. The set of skew symmetric matrices \( S \) that satisfy the following equation:

\[
BB^\dagger SBB^\dagger = S, \quad (\text{or equivalently } BB^\dagger S = S)
\]

is denoted by \( \text{Skew}(n; B) \).

Here, \( \dagger \) represents a pseudo (Moore-Penrose) inverse of matrix.

Proposition 1. (Parametrization of \( \mathcal{F}_S(A, B) \))

i) Let \( Q \) be in \( PD(n) \). All stabilizing state feedback gains \( F \in \mathcal{F}_S(A, B) \) are parametrized by

\[
F = -B^\dagger (AP + PA^T + Q) \left( I - \frac{1}{2} BB^\dagger \right) P^{-1} - B^\dagger S P^{-1}
\]

using \( P \in PD(n; A, B, Q) \) and \( S \in \text{Skew}(n; B) \).

ii) The mapping \( \psi_Q : PD(n; A, B, Q) \times \text{Skew}(n; B) \rightarrow \mathcal{F}_S(A, B) \) defined by (2.4) is diffeomorphic.

iii) The feedback gain \( F \) represented as (2.4) satisfies the following Lyapunov equation:

\[
(A + BF)P + P(A + BF)^T + Q = 0
\]

for \( P \in PD(n; A, B, Q) \) that is just parametrizing \( F \) in (2.4).
Proposition 2.

i) The set PD(n; A, B, Q) is an \(mn(m-1)/2\) (\(= N_P\))-dimensional submanifold of PD(n).

ii) The set Skew(n; B) is an \(m(m-1)/2\) (\(= N_S\))-dimensional vector subspace of Skew(n).

Proposition 3. (Parametrization of \(S(n)\))

i) Let \(Q\) be in PD(n). All stable matrices \(A_S \in S(n)\) are parametrized by

\[ A_S = -\frac{1}{2}QP^{-1} + S P^{-1} \]  \hspace{1cm} (2.5)

using \(P \in PD(n)\) and \(S \in Skew(n)\).

ii) The mapping \(\phi_Q : PD(n) \times Skew(n) \rightarrow S(n)\) defined by (2.5) is diffeomorphic.

iii) The stable matrix \(A_S\) represented as (2.5) satisfies the following Lyapunov equation:

\[ A_S P + PA_S^T + Q = 0. \]

Remark 1. Proposition 3ii) shows that the set \(S(n)\) can be treated as a vector bundle that consists of \(PD(n)\) as a base manifold and \(Skew(n)\) as a fibre of vector space. We use a notation \(Skew_P(n)\) to represent each fibre attached to the element \(P\) in the base manifold \(PD(n)\). Each fibre \(Skew_P(n)\) has its own metric depending on \(P\) (Theorem 3.2). This is one of the main reasons why we will treat \(PD(n) \times Skew(n)\) as a vector bundle rather than a mere product set. The interpretation of decomposition (2.5) from point of view of system dynamics is discussed in [6,9].

Define the set of state feedback system matrices as

\[ S_f(A, B) := \{ A + BF \mid F \in F_S(A, B) \} \subset S(n) \]

and a mapping

\(\chi : F_S(A, B) \ni F \mapsto A + BF \in S_f(A, B)\).

Using \(\phi_Q^{-1}\), we can characterize structures of \(S_f(A, B)\) in \(PD(n) \times Skew(n)\).

From (2.4) we can get

\[ A + BF = -\frac{1}{2}QP^{-1} + (S_0(P) - S)P^{-1}, \]  \hspace{1cm} (2.6)

where

\[ S_0(P) := AP - BB^T (AP + PA^T + Q) \left(I - \frac{1}{2}BB^T\right) + \frac{1}{2}Q, \]  \hspace{1cm} (2.7)

\(P \in PD(n, A, B, Q), \quad S \in Skew(n, B)\).

Since \(P \in PD(n, A, B, Q)\), \(S_0(P)\) is proved to be skew symmetric using (2.2) and so is \(S_0(P) - S\).

Let \(Skew_P(n, B)\) denote the set of all \(S \in Skew_P(n)\) that satisfy (2.3). Comparing (2.5) and (2.6), we find how \(S_f(A, B)\) is imbedded in \(PD(n) \times Skew(n)\) by \(\phi_Q^{-1}\).
Proposition 4. The set of stable state feedback system matrices $S_f(A, B)$ is imbedded in the vector bundle $PD(n) \times Skew(n)$ as follows:

i) in the base manifold $PD(n)$, $S_f(A, B)$ is restricted to the submanifold $PD(n; A, B, Q)$,

ii) in each fibre $Skew_P(n)$ such that $P \in PD(n; A, B, Q)$, $\phi_Q^{-1}(S_f(A, B))$ is restricted to $S_0(P) + Skew_P(n; B)$.

In other words, $S_f(A, B)$ is diffeomorphic to a submanifold

$$\phi_Q^{-1}(S_f(A, B)) = \bigcup_{P \in PD(n; A, B, Q)} \{S_0(P) + Skew_P(n; B)\}, \quad (2.8)$$

contained in $PD(n) \times Skew(n)$. (See Figure 1).

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Example 1. Consider the following linear system:

$$\dot{x}(t) = Ax(t) + Bu(t), \quad \text{where} \quad A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}.$$
Differential Geometric Structures of Stable State Feedback Systems with Dual Connections

It is easily verified that \((A, B)\) is controllable and \(B\) is of full column rank. Define 
\[
Q = I \in \mathbb{R}^{3 \times 3}
\]
and represent \(P \in PD(3)\) and \(S \in \text{Skew}(3)\) as 
\[
P = \begin{bmatrix}
\eta_1 & \eta_2 & \eta_3 \\
\eta_2 & \eta_4 & \eta_5 \\
-\frac{1}{2} & \eta_6 & \eta_6
\end{bmatrix},
S = \begin{bmatrix}
0 & -\zeta_1 & -\zeta_2 \\
\zeta_1 & 0 & -\zeta_3 \\
\zeta_2 & \zeta_3 & 0
\end{bmatrix}.
\]

Then we can obtain the parameter set \(PD(3; A, B, I)\) and \(\text{Skew}(3; B)\) as follows:

Calculate (2.2) and (2.3) using the pseudo-inverse matrix of \(B\):
\[
B^T = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0
\end{bmatrix},
\]
then we get \(\eta_3 = -\frac{1}{3}\) and \(\zeta_3 = \zeta_3 = 0\). Thus, any \(P \in PD(3; A, B, I)\) and \(S \in \text{Skew}(3, B)\) are of the forms:
\[
P = \begin{bmatrix}
\eta_1 & \eta_2 & -\frac{1}{2} \\
\eta_2 & \eta_4 & \eta_5 \\
-\frac{1}{2} & \eta_6 & \eta_6
\end{bmatrix},
S = \begin{bmatrix}
0 & -\zeta_1 & 0 \\
\zeta_1 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}.
\]

Hence, all stabilizing state feedback gains of \((A, B)\) are expressed using (2.4) and \(P, S\) of (2.9) as 
\[
F = \psi_1(P, S) = \begin{bmatrix}
-\frac{1}{3} & \frac{1}{4} + \zeta_1 & -\eta_1 \\
\frac{1}{4} - \zeta_1 & -\frac{1}{3} - \eta_5 & -\eta_2 - \eta_6 \\
\frac{1}{3} - \frac{1}{2} & \eta_5 & \eta_6
\end{bmatrix}^{-1}.
\]

From (2.9), we can examine the number of free parameters of \(PD(3; A, B, I)\) and that of \(\text{Skew}(3; B)\) are 5 and 1, respectively. These are equal to the dimension of \(PD(3; A, B, I)\) and \(\text{Skew}(3; B)\) calculated by Proposition 2.

Finally, we can obtain \(S_0(P) \in \text{Skew}(3)\) from (2.7) as 
\[
S_0(P) = \begin{bmatrix}
0 & \frac{1}{4} & -\eta_1 \\
-\frac{1}{4} & 0 & -\eta_2 \\
\eta_1 & \eta_2 & 0
\end{bmatrix},
\]
and \(S_0(P) + \text{Skew}_P(n; B)\) is the set of skew symmetric matrices of the form:
\[
\begin{bmatrix}
0 & \frac{1}{4} + \zeta_1 & -\eta_1 \\
-\frac{1}{4} - \zeta_1 & 0 & -\eta_2 \\
\eta_1 & \eta_2 & 0
\end{bmatrix}
\]

included in the fibre \(\text{Skew}_P(n)\). Then, all stable state feedback systems are expressed using (2.6) as 
\[
A+B F = \psi_2 (P, S_0(P) - S) = \begin{bmatrix}
-\frac{1}{3} & \frac{1}{4} + \zeta_1 & -\eta_1 \\
-\frac{1}{4} - \zeta_1 & -\frac{1}{3} - \eta_5 & -\eta_2 - \eta_6 \\
\eta_1 & \eta_2 & \eta_3
\end{bmatrix}^{-1}.
\]

The set of \(PD(3; A, B, I) \times \text{Skew}(3; B)\) is imbedded in \(PD(3) \times \text{Skew}(3)\) in this way.
3. TRANSFORMATION INVARIANT METRICS

To explore metric structures of \( PD(n) \times \text{Skew}(n) \), we introduce metrics to two vector bundles. One is a tangent bundle \( TPD(n) = \bigcup_{P \in PD(n)} TPD(n) \), where \( TPD(n) \) denotes the tangent vector space at a point \( P \in PD(n) \). The other is \( PD(n) \times \text{Skew}(n) = \bigcup_{P \in PD(n)} \text{Skew}(n) \) itself. A metric \( g(P) \) of \( TPD(n) \) is called a Riemannian metric on \( PD(n) \) and we refer to a metric \( f(P) \) of \( PD(n) \times \text{Skew}(n) \) as a fibre metric.

For the basis transformations of state space, \( \tilde{\xi}(t) = T \xi(t) \), where \( T \in GL(n; \mathbb{R}) \), the matrices \( P \) and \( S \) in the parametrization are transformed congruently as
\[
(P, S) \rightarrow (TPT^T, TST^T).
\]

For consistency with linear systems theory, we should define metrics on \( PD(n) \times \text{Skew}(n) \) invariant against the above congruent transformations.

3.1. Transformation invariant Riemannian metric on \( PD(n) \)

Let \( E_{pq} \) be the matrix with one as the \((p, q)\)th element and zero otherwise. Now, we define \( E_i \), the basis matrices of vector space \( \text{Sym}(n) \), by
\[
E_i := E_{\sigma(p,q)} = \begin{cases} E_{pp}, & p = q, \\ E_{pq} + E_{qp}, & p < q. \end{cases}
\]

Here, \( \sigma \) is an appropriate rule to assign integers to the pairs \((p, q)\), i.e. \( \sigma(p, q) = i \), where \( 1 \leq p \leq q \leq n \) and \( 1 \leq i \leq N := n(n+1)/2 \).

Using \( E_i \), we can represent any \( P \in PD(n) \) as \( P = \sum_{i=1}^{N} \eta^i E_i \) uniquely, where \( (\eta^i) \) belong to some open subset of \( \mathbb{R}^N \) that satisfies the positive definiteness. Hence, we consider \( (\eta^i) \) as a global coordinate system of \( N \)-dimensional manifold \( PD(n) \). Then, natural basis of tangent vector fields \( \partial_i := \partial / \partial \eta^i \) can be identified with \( E_i \), i.e.,
\[
X(PD(n)) \ni \partial_i \sim E_i \in \text{Sym}(n), \quad 1 \leq i \leq N,
\]
where \( X(PD(n)) \) denotes the set of tangent vector fields on \( PD(n) \). Using (3.2), we shall hereafter identify \( X(PD(n)) \) with the set of \( \text{Sym}(n) \)-valued differentiable function \( X(P) \) on \( PD(n) \):
\[
X(PD(n)) \ni \sum_{i=1}^{N} a^i(P) \partial_i \sim X(P) := \sum_{i=1}^{N} a^i(P) E_i, \quad a^i(P) \in \mathcal{C}(PD(n)),
\]
where \( \mathcal{C}(PD(n)) \) denotes the set of differentiable functions on \( PD(n) \). Similarly we shall identify the tangent vector space at \( P \), which is denoted by \( TPD(n) \), with \( \text{Sym}(n) \):
\[
X_P := \sum_{i=1}^{N} a^i \left( \frac{\partial}{\partial \eta^i} \right)_P \in TPD(n) \sim X := \sum_{i=1}^{N} a^i E_i \in \text{Sym}(n), \quad a^i \in \mathbb{R}.
\]
First we shall make clear what invariance is required for a Riemannian metric on $PD(n)$. A Riemannian metric $g(P) = [g_{ij}(P)]$ defines an inner product $g_P(\cdot, \cdot)$ on each tangent space $T_P PD(n)$. To represent $g_P(\cdot, \cdot)$ as an inner product of $\text{Sym}(n)$, we use the same notation. Then these inner products are defined by

$$g_P(\partial_i, \partial_j) = g_P(E_i, E_j) := g_{ij}(P), \quad 1 \leq i \leq N, \ 1 \leq j \leq N. \quad (3.4)$$

Denote the congruent transformation (3.1) by

$$\tau_T : P \rightarrow TPT^T, \quad T \in \text{GL}(n; \mathbb{R}), \quad (3.5)$$

which is induced by the basis transformation of the state space (1.11). Then using the identification (3.3), the differential $\tau_T : T_P PD(n) \rightarrow T_{\tau_T(P)} PD(n)$ is represented as a transformation in $\text{Sym}(n)$ by

$$\tau_T : X \mapsto TXX^T, \quad (3.6)$$

where $X$ and $TXX^T$ indicate $X_P \in T_P PD(n)$ and $\tau_T(X_P) \in T_{\tau_T(P)} PD(n)$, respectively.

The invariance we require here of a Riemannian metric $g(P)$ is that the following equation:

$$g_P(X_P, Y_P) = g_{\tau_T(P)}(\tau_{T^*}(X_P), \tau_{T^*}(Y_P)) \quad (3.7)$$

should be satisfied for any $P \in PD(n)$, $X_P, Y_P \in T_P PD(n)$ and $T \in \text{GL}(n; \mathbb{R})$.

This is equivalent to

$$g_P(X, Y) = g_{TPT^T}(TX^T, TY^T) \quad (3.8)$$

for any $P \in PD(n)$, $X, Y \in \text{Sym}(n)$ and $T \in \text{GL}(n; \mathbb{R})$.

Now the invariant Riemannian metric on $PD(n)$ is obtained.

Theorem 3.1. Define $g_{ij}(P)$ by

$$g_{ij}(P) := \frac{1}{2} \text{tr} (P^{-1}E_iP^{-1}E_j), \quad (3.9)$$

then $g(P) = [g_{ij}(P)]$ is a Riemannian metric on $PD(n)$ invariant under the basis transformation of the state space.

Proof. Because of (3.4) and (3.9), the inner product on $\text{Sym}(n)$ is represented by

$$g_P(X, Y) = \frac{1}{2} \text{tr} (P^{-1}XP^{-1}Y). \quad (3.10)$$

Hence the invariance condition (3.8) can be easily confirmed as

$$g_{TPT^T}(TX^T, TY^T) = \frac{1}{2} \text{tr} \left( T^{-T}(P^{-1}XP^{-1}Y)T^T \right)$$

$$= \frac{1}{2} \text{tr} \left( (P^{-1}XP^{-1}Y) TT^{-T} \right) = g_P(X, Y). \quad (3.11)$$
To show the positive definiteness of $g_{ij}(P)$, consider the basis transformation $T \in GL(n; \mathbb{R})$ satisfying $TP^T = I$. (3.12)

Let $X := \sum_{i=1}^{N} d_i E_i$, then from the invariance we can get

$$g_P(X, X) = \sum_{i,j=1}^{N} g_{ij}(P) d_i^2 = \frac{1}{2} \text{tr} \left\{ (P^{-1} X)^2 \right\} = \frac{1}{2} \text{tr}(X^2), \quad X' := TX^T.$$

Since $X'$ is also a symmetric matrix, $\text{tr}(X^2)$ is identical to the square of the Euclid norm of $X'$, which is always positive except that $X' = 0$. This means $g_{ij}(P)$ is positive definite. Moreover, the differentiability of $g_{ij}(P)$ follows from that of $P^{-1}$.

Thus, $g(P)$ is proved to be an invariant Riemannian metric on $PD(n)$. \( \square \)

**Example 2.** We shall calculate the Riemannian metric on $PD(2)$. Set $\{E_i\}$ as

$$E_1 := \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \quad E_2 := \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad E_3 := \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix},$$

then $P$ can be represented using coordinate system $(\eta^t)$ as

$$P := \begin{bmatrix} \eta^1 \\ \eta^2 \\ \eta^3 \end{bmatrix}.$$

From the result of Theorem 3.1, we obtain invariant Riemannian metric on $PD(2)$ as

$$[g_{ij}(P)] = \frac{1}{(\eta^1)^2 - (\eta^2)^2} \begin{bmatrix} (\eta^3)^2 & -2\eta^3\eta^2 & 2\{(\eta^2)^2 + \eta^1\eta^3\} \\ -2\eta^3\eta^2 & (\eta^3)^2 & -2\eta^1\eta^2 \\ 2\{(\eta^2)^2 + \eta^1\eta^3\} & -2\eta^1\eta^2 & (\eta^3)^2 \end{bmatrix}.$$

Let $P(t) = (\eta^t(t))$, $a \leq t \leq b$ be a differentiable curve on $PD(n)$. The arc length $L$ of $P(t)$ is defined by

$$L := \int_{P(t)} ds = \int_{a}^{b} \left\{ \sum_{i} g_{ii}(p(t)) \frac{dp^i}{dt} \frac{dp^i}{dt} \right\}^{1/2} dt$$

and distance between two points is usually defined by the infimum of the lengths of all differentiable curves connecting them. The distance defined like this is, of course, invariant under the state-space basis transformation. Since the manifold $PD(n)$ equipped with Riemannian metric $g_{ij}(P)$ defined in Theorem 3.1 is proved to be Riemannian (globally) symmetric space [11,12], we can give the distance function explicitly:

**Theorem 3.2.** Assume $P_1$ and $P_2$ are in the Riemannian manifold $(PD(n), g)$ where $g$ is defined in Theorem 3.1. The invariant distance between the points $P_1$ and $P_2$ is given by

$$\text{dist}(P_1, P_2) = \left\{ \text{tr}[(\log P_T)^2] \right\}^{1/2}, \quad \text{where} \ P_T := P_1^{-\frac{1}{2}} P_2 P_1^{-\frac{1}{2}}.$$

**Proof.** See the Appendix.
3.2. Transformation invariant fibre metric of $PD(n) \times \text{Skew}(n)$

On the other hand, define the basis matrices $\tilde{E}_\mu$ of $n(n - 1)/2$-dimensional vector space $\text{Skew}(n)$ by

$$\tilde{E}_\mu := \tilde{E}_{\sigma(p,q)} = E_{pq} - E_{qp}, \quad p < q,$$

where $\widetilde{\sigma}$ is an appropriate rule to assign integers to the pair $(p, q)$, i.e. $\widetilde{\sigma}(p, q) = \mu$, where $1 \leq p < q \leq n$ and $1 \leq \mu \leq \tilde{N} := n(n - 1)/2$. Then any skew symmetric matrix $S = (\tilde{\eta}^\mu)$ in each fibre space $\text{Skew}_P(n)$ is represented by

$$S = \sum_{\mu=1}^{\tilde{N}} \tilde{\eta}^\mu \tilde{E}_\mu, \quad \tilde{\eta}^\mu \in \mathbb{R}.$$

Furthermore, a $\text{Skew}(n)$-valued differentiable function $S(P)$ on $PD(n)$ is just a cross section of $PD(n) \times \text{Skew}(n)$:

$$S(P) = \sum_{\mu=1}^{\tilde{N}} \tilde{\eta}^\mu(P) \tilde{E}_\mu \in \Gamma(PD(n) \times \text{Skew}(n)), \quad \tilde{\eta}^\mu(P) \in C(PD(n)),$$

where $\Gamma(PD(n) \times \text{Skew}(n))$ denotes the set of cross sections of $PD(n) \times \text{Skew}(n)$. We regard $\tilde{E}_\mu$ as a (constant) basis cross section.

A fibre metric $f(P) = [f_{\mu\lambda}(P)]$ defines an inner product $f_P(\cdot, \cdot)$ on each fibre $\text{Skew}_P(n)$

$$f_P(\tilde{E}_\mu, \tilde{E}_\lambda) := f_{\mu\lambda}(P), \quad \tilde{E}_\mu, \tilde{E}_\lambda \in \text{Skew}_P(n).$$

Note that the basis transformation of the state space causes the congruence transformation which maps $S \in \text{Skew}_P(n)$ to $TST^T \in \text{Skew}_{TPPT}(n)$, or equivalently,

$$\tau_T : (P, S) \mapsto (TPT^T, TST^T).$$

Then we find a fibre metric $f_{\mu\lambda}(P)$ is required to satisfy the invariance such that

$$f_P(S, R) = f_{TPTT}(TST^T, TRT^T)$$

for any $P \in PD(n)$, $S, R \in \text{Skew}_P(n)$ and $T \in \text{GL}(n; \mathbb{R})$.

An invariant fibre metric $f(P) = [f_{\mu\lambda}(P)]$ can be derived in the similar manner to Theorem 3.1.

Theorem 3.3. Define $f_{\mu\lambda}(P)$ by

$$f_{\mu\lambda}(P) := -\frac{1}{2} \text{tr} \left( P^{-1} \tilde{E}_\mu P^{-1} \tilde{E}_\lambda \right),$$

then $f(P) = [f_{\mu\lambda}(P)]$ is a fibre metric of $PD(n) \times \text{Skew}(n)$ invariant under the basis transformation of the state space.
Proof. The invariance and the differentiability of $f_{\mu}(P)$ are proved in the same way of Theorem 2. In contrast to Theorem 2, skew symmetry guarantees the positive definiteness. Consider the same basis transformation (3.12), then

$$f_{\mu}(S, S) = \sum_{\mu, \lambda=1}^q f_{\mu\lambda}(P) \bar{\eta}^\mu \bar{\eta}^\lambda = -\frac{1}{2} \text{tr} \{(P^{-1}S)^2\} = -\frac{1}{2} \text{tr}(S^T S) = \frac{1}{2} \text{tr}(S^T S') = \frac{1}{2} \|S\|^2.$$

Hence, $f(P) = [f_{\mu}(P)]$ is positive definite. $\Box$

4. DUAL CONNECTIONS ON $PD(n) \times \text{Skew}(n)$

Let $t$ be in an interval $[0, t_1] \subset \mathbb{R}$ and $c : t \mapsto c(t) = P(t)$ be a smooth curve in $PD(n)$ from $P_0$ to $P_1$. For all $t$, consider a linear isomorphism $\Pi_t(t) : T_{P(t)}PD(n) \rightarrow T_{P(t)}PD(n)$ called a parallel displacement along the curve $c$. Let $X(P)$ be a tangent vector field on $PD(n)$, then covariant derivative at $P_0$ for the direction $c(0) = P(0)$ is obtained from the parallel displacement $\Pi_{c}(t)$ as

$$\nabla_{P(0)}X = \lim_{t \rightarrow 0} \frac{1}{t} \{\Pi_{c}(t)^{-1}X(P(t)) - X(P_0)\}.$$

Using the parallel displacement along all the smooth curve on $PD(n)$, we can define the covariant derivative vector field on $PD(n)$.

In the same way, a parallel displacement along the curve $c$ can be introduced to the vector bundle $PD(n) \times \text{Skew}(n)$. It is characterized as a linear isomorphism $\tilde{\Pi}_t(t) : \text{Skew}_{P_0}(n) \rightarrow \text{Skew}_{P(t)}(n)$, and the corresponding covariant derivative for a cross section $S(T) \in \Gamma(PD(n) \times \text{Skew}(n))$ is expressed by

$$\tilde{\nabla}_{P(0)}S = \lim_{t \rightarrow 0} \frac{1}{t} \{\tilde{\Pi}_{c}(t)^{-1}S(P(t)) - S(P_0)\}.$$

The above shows that if parallel displacements $\Pi$ in $T PD(n)$ and $\tilde{\Pi}$ in $PD(n) \times \text{Skew}(n)$ are defined for any piecewise smooth curve $c$ in $PD(n)$, we can derive affine connections $\nabla$ of $T PD(n)$ and fibre connections $\tilde{\nabla}$ of $PD(n) \times \text{Skew}(n)$, respectively.

Consider two parallel displacements $\Pi$ and $\tilde{\Pi}$ of $T PD(n)$ defined by

$$\Pi(t)X = X, \quad \tilde{\Pi}(t)X = P(t) P_0^{-1} X P_0^{-1} P(t), \quad (4.1)$$

for any curve $c$ and $X \in \text{Sym}(n)$ using the identification (3.3). Let $\nabla$ and $\tilde{\nabla}^*$ denote the corresponding affine connections. It is easily proved from (3.9) that these two parallel displacements satisfy

$$g_{P_0}(X, Y) = g_{P(t)}(\Pi(t)X, \tilde{\Pi}(t)Y), \quad \forall X, Y \in \text{Sym}(n).$$

Such a pair of parallel displacements $(\Pi, \tilde{\Pi}^*)$ and a pair of the derived connections $(\nabla, \tilde{\nabla}^*)$ are said to be mutually dual [8]. The obtained results are as follows.
Theorem 4.1. The covariant derivatives with respect to the parallel displacements $\Pi_c$ and $\Pi_c^*$ satisfy
\[
\nabla_{E_i} E_j = 0, \quad \nabla_{E_i}^* E_j = -E_i P^{-1} E_j - E_j P^{-1} E_i,
\]
respectively. Here, we are identifying the vector field $\partial / \partial \eta^i$ and $E_i$.

Proof. Since the parallel displacement $\Pi_c$ does not change basis tangent vectors as $\Pi_c E_i = E_i$, the equation $\nabla_{E_i} E_j = 0$ is obvious.

To obtain the $\nabla_{E_i}^* E_j$, we consider the curve $\gamma : P(t)$ defined by
\[
P(t) := \tau_{p(t)} \exp(Xt) = P^1 \exp(Xt) P^1.
\]
The curve $\gamma : P(t)$ is found to satisfy
\[
P(0) = 0 \quad \text{and} \quad \dot{P}(0) = \tau_{p(t)} X = P^1 X P^1,
\]
where $\tau_{p(t)} X$ is the differential of $\tau_{p(t)}$. Hence, to calculate the covariant derivative $\nabla_{E_i}^* E_j$ using the curve $\gamma : P(T)$, we shall set
\[
X := \dot{p}(t) = P^{-\frac{1}{2}} E_i P^{-\frac{1}{2}}.
\]

Then from the definition of covariant derivative,
\[
\nabla_{E_i}^* E_j = \lim_{t \to 0} \frac{1}{t} \left\{ \Pi_c^*(t)^{-1} E_j - E_j \right\}.
\]

Since $\Pi_c^*(t)^{-1} E_j$ is represented via (4.1) and (4.3) by
\[
\Pi_c^*(t)^{-1} E_j = P P(t)^{-1} E_j P(t)^{-1} P = P^1 \exp(-Xt) P^{-\frac{1}{2}} E_j P^{-\frac{1}{2}} \exp(-Xt) P^\frac{1}{2},
\]
we substitute this expression in (4.4) to get
\[
\nabla_{E_i}^* E_j = \frac{d}{dt} \left\{ P^1 \exp(-Xt) P^{-\frac{1}{2}} E_j P^{-\frac{1}{2}} \exp(-Xt) P^\frac{1}{2} \right\}_{t=0} =
\[
= -P^\frac{1}{2} X P^{-\frac{1}{2}} E_j - E_j P^{-\frac{1}{2}} X P^\frac{1}{2}
\]
\[
= -E_i P^{-1} E_j - E_j P^{-1} E_i.
\]

Theorem 4.2.

i) The manifold $PD(n)$ is torsion free and flat with respect to the affine connection $\nabla$. (We shall call the latter properties $\nabla$-flat.

ii) The manifold $PD(n)$ is torsion free and flat with respect to the affine connection $\nabla^*$. (We shall call the latter properties $\nabla^*$-flat.)

Proof. 

i) From (4.2), the coefficients of affine connection $\nabla$, which are defined by $\Gamma_{ijk} := g_p(\nabla_{E_i} E_j, E_k)$, vanish. This means the statement i).
First, let $T^*(\cdot,\cdot)$ be the torsion tensor of the affine connection $\nabla^*$. We have

$$T^*_{jk} := g_P (T^*(E_i, E_j), E_k) = g_P \left( \nabla^*_E E_j - \nabla^*_E E_i, E_k \right).$$

Here, the coefficients of affine connection $\nabla^*$ denoted by $\Gamma^*_{ijk}$ is obtained by

$$\Gamma^*_{ijk}(P) := g_P (\nabla^*_E E_j, E_k) = \frac{1}{2} \text{tr} \left\{ P^{-1} (-E_i P^{-1} E_j - E_j P^{-1} E_i) P^{-1} E_k \right\}$$

using the symmetry of $P$, $E_i$, $E_j$ and $E_k$. Hence, we get

$$T^*_{jk}(P) = \Gamma^*_{ijk}(P) - \Gamma^*_jik(P) = 0.$$

Secondly, recall the definition of $\Pi^*$, then we find it depends not on the curve it passes along but on the points where it starts and finishes. Furthermore, when the curve is closed, $\Pi^*$ is proved to map a tangent vector $X \in T_p PD(n)$ to itself. This means ii) is true because the curvature tensors are geometrically interpreted as changes of tangent vectors by parallel displacements along infinitesimally small closed curves. Thus the statement ii) follows. □

Similarly a pair of parallel displacements $(\Pi^*_e, \Pi^*_*)$ for any curve can be defined on $PD(n) \times \text{Skew}(n)$:

$$\Pi^*_e(t) S = S, \quad \Pi^*_*(t) S = P(t) P_0^{-1} S P_0^{-1} P(t).$$

And we shall also call $(\Pi^*_e, \Pi^*_*)$, or a pair of the corresponding fibre connections $(\nabla, \nabla^*)$, mutually dual because they satisfy

$$f_{P_0}(S, R) = f_P \left( \Pi^*_e(t), S, \Pi^*_*(t) R \right), \quad \forall S, R \in \text{Skew} P_0(n).$$

We can show the followings similarly to Theorem 4.1 and 4.2.

**Theorem 4.3.** The covariant derivatives with respect to the parallel displacements $\Pi^*_e$ and $\Pi^*_*$ satisfy

$$\tilde{\nabla}_{E_i} \tilde{E}_\mu = 0, \quad \tilde{\nabla}^*_R \tilde{E}_\mu = -E_i P^{-1} \tilde{E}_\mu - \tilde{E}_\mu P^{-1} E_i,$$

respectively. Here, we are identifying $\tilde{E}_\mu$ as the basis cross section.

**Theorem 4.4.** The vector bundle $PD(n) \times \text{Skew}(n)$ is flat with respect to both fibre connections $\nabla$ and $\nabla^*$. We shall call these properties $\nabla$-flat and $\nabla^*$-flat, respectively.
Remark 2. Both $\nabla$ and $\nabla^*$ are non-metric affine connections. However, we see they qualify $PD(n)$ as a torsion free, flat manifold in Theorem 4.2. Similarly, non-metric fibre connections $\nabla$ and $\nabla^*$ endow the vector bundle $PD(n) \times Skew(n)$ with flatness.

The coordinate system $(\eta^i)$ is called affine with respect to $\nabla$ because its basis vector fields satisfy $\nabla E_j = 0$. The coordinate system $(\bar{\eta}^a)$ is also natural with respect to $\nabla$ in the sense that its basis cross sections satisfy $\nabla E_\mu = 0$. On the other hand, we can also introduce affine and "natural" coordinate systems with respect to $\nabla^*$ and $\nabla^*$. These coordinate systems are called dual coordinate systems [8]. Such a pair of primal and dual coordinate systems plays important roles in the theory of dual connections, e. g., defining a pseudo-distance called divergences [8].

Another remark is that we can define the family of connections using $(\nabla, \nabla^*)$ and $(\nabla, \nabla^*)$ in the same way to [8]. Define the connections depending one parameter $\alpha \in \mathbb{R}$ by

$$\nabla_{\alpha} := \frac{1}{2} \nabla + \frac{1}{2} \nabla^*, \quad \nabla^*_{\alpha} := \frac{1}{2} \nabla + \frac{1}{2} \nabla^*.$$

We call $\nabla$ and $\nabla^*$ $\alpha$-affine and $\alpha$-fibre connections, respectively. The pairs of connections $(\nabla, \nabla^*)$ and $(\nabla, \nabla^*)$ are mutually dual, respectively. Particularly, affine connection $\nabla$ and fibre connection $\nabla^*$ are metric. It is well known that $\nabla$ is called Riemannian (Levi-Civita) connection of $PD(n)$.

5. DIFFERENTIAL GEOMETRY OF PARAMETER SPACE FOR $\mathcal{F}_S(A, B)$ AND $\mathcal{S}_f(A, B)$

In the previous sections, we have defined metrics and connections, the fundamental quantities for the differential geometric structures of $PD(n) \times Skew(n)$. Now using these quantities, we shall exploit the geometric structures of vector bundle $PD(n; A, B, Q) \times Skew(n; B) = \psi_Q^{-1}(\mathcal{F}_S(A, B))$, which parametrizes $\mathcal{F}_S(A, B)$ and imbedded submanifold $\phi_Q^{-1}(\mathcal{S}_f(A, B))$ in $PD(n) \times Skew(n)$, which parametrizes $\mathcal{S}_f(A, B)$.

In this section, indices $\{i, j, \ldots\}, \{a, b, \ldots\}$ and $\{\alpha, \beta, \ldots\}$ attached to quantities means that the quantities are components with respect to $PD(n)$, $PD(n; A, B, Q)$, $Skew(n)$ and $Skew(n; B)$, respectively.

5.1. Geometry of $PD(n; A, B, Q) \times Skew(n; B)$ induced from $PD(n) \times Skew(n)$

Using the equation (2.2) which specifies the submanifold $PD(n; A, B, Q)$ in $PD(n)$, we first construct the coordinate system $(\gamma^a)$ for $PD(n; A, B, Q)$ and then define induced Riemannian metric and connections.

Since (2.2) is linear equations with respect to the components of $P$, i.e.,

$$\eta = (\gamma^a) \in \mathbb{R}^N,$$

then it can be rewritten as

$$K \eta = w,$$

(5.1)
where $K \in \mathbb{R}^{(N-N_P) \times N}$, $w \in \mathbb{R}^{N-N_P}$ are some constant matrix and vector determined from (2.2) [6].

Let $T$ be in $GL(N; \mathbb{R})$ which satisfies $KT = [I \ 0]$ and define $\eta' := T^{-1} \eta$. Then (5.1) is transformed and solved as

$$[I \ 0] \eta' = w, \quad \eta' = \begin{bmatrix} w \\ \gamma \end{bmatrix}. $$

The free parameter $\gamma = (\gamma^a) \in \mathbb{R}^{N_r}$ is just the coordinate system of the submanifold $PD(n; A, B, Q)$. The relation between $(\eta')$ and $(\gamma^a)$ is

$$\eta(\gamma) = T \eta' = [T_1 \ T_2] \begin{bmatrix} w \\ \gamma \end{bmatrix}. $$

Hence, the Jacobian matrix $J := (\partial \eta^i / \partial \gamma^a) = T_2$ is a constant matrix. Then, the relation between basis tangent vector fields $E_i$ of $PD(n)$ and $E_a \sim \partial / \partial \gamma^a$ of $PD(n; A, B, Q)$ is found to be $E_a = J_a^i E_i$.

Using this relation, geometrical quantities on submanifold $PD(n; A, B, Q)$ are naturally induced from those of $PD(n)$. The induced metric $g_{ab}(\gamma)$ on $PD(n; A, B, Q)$ is given by

$$(5.2) \quad g_{ab}(\gamma) = J_b^j J_a^i g_{ij}(\gamma). $$

Generally, the coefficients $\Gamma_{abc}(\gamma)$ of induced affine connections are obtained by

$$(5.3) \quad \Gamma_{abc}(\gamma) = g_{PQR} \left( \nabla_{E_a} E_b, E_c \right) = J_a^j J_b^k J_c^l (\Gamma_{ijk}(\gamma) + (\partial_a J_b^i) J_c^l g_{ij}(\gamma)), $$

where $\Gamma_{ijk}(\gamma)$ is the coefficients of any affine connection on $PD(n)$.

By means of (5.2), (5.3), we can obtain the following results:

**Theorem 5.1.** $PD(n; A, B, Q)$ is $\nabla$-flat and $\nabla^*$-flat manifold in itself, namely its Riemann–Christoffel curvature tensor $R_{abcd}$ and $R^*_{abcd}$ vanish.

**Proof.** Since Jacobian matrix $J$ in (5.3) is constant, its partial derivatives by $\gamma^a$ vanish, $\partial_a J_b^i = 0$. From this and $\Gamma_{ijk} = 0$ (Theorem 4.1), (5.3) means $\Gamma_{abc} = 0$, i.e., the coefficients of affine connection for submanifold $PD(n; A, B, Q)$ vanish. Since Riemann–Christoffel curvature tensors of $\nabla$-connection $R_{abcd}$ is defined by

$$R_{abcd} = g_{PQR} \left( R(E_a, E_b) E_c, E_d \right) = (\partial_a \Gamma_{bc}^e - \partial_b \Gamma_{ac}^e + \Gamma_{ade} \Gamma_{bc}^e - \Gamma_{ace} \Gamma_{bd}^e), $$

it also vanishes. This shows $PD(n; A, B, Q)$ is $\nabla$-flat. The $\nabla^*$-flatness follows automatically from $\nabla$-flatness [8].

In the same way, using the equation (2.3) specifying $Skew(n; B)$, we can construct the coordinate system $\tilde{\gamma} = (\tilde{\gamma}^a) \in \mathbb{R}^{N_r}$ of $Skew(n; B)$. In this fibre case, constant Jacobian matrix denoted by $\tilde{J}$ is also obtained: $\tilde{\eta} = \tilde{J} \tilde{\gamma}$.

We can induce fibre metrics and connections on $PD(n; A, B, Q) \times Skew(n; B)$. Since $\tilde{J}$ is constant,

$$f_{ab}(\gamma) = J_a^i J_b^j f_{\alpha \beta}(\eta), \quad \tilde{f}_{ab}(\gamma) = \tilde{J}_a^i \tilde{J}_b^j \tilde{f}_{\alpha \beta}(\eta). $$

Then we can show the following similarly to Theorem 5.1.
Theorem 5.2. The vector bundle $PD(n; A, B, Q) \times \text{Skew}(n; B)$ is $\nabla$- and $\tilde{\nabla}^*$-flat vector bundle in itself, i.e., its curvatures vanish.

5.2. Geometry of $\phi_Q^{-1}(S_f(A, B))$ imbedded in $PD(n) \times \text{Skew}(n)$

In section 2, we have seen $S_f(A, B)$ is imbedded in $PD(n) \times \text{Skew}(n)$ by $\phi_Q$ as (2.8). We can get some results using this imbedding.

To see the structures of $PD(n; A, B, Q)$ as a canonically imbedded submanifold in $PD(n)$, it is enough to calculate Euler–Schouten (imbedding) curvature tensor. Let $\{E_k\} (k = N + 1, \ldots, N)$ be the basis of orthogonally complement subspace of $TP PD(n; A, B, Q)$ in $TP PD(n)$, then Euler–Schouten curvature tensor $H_{abk}$ is defined by

$$H_{abk} = g_F (\nabla_{E_a} E_b, E_k), \quad H^*_{abk} = g_F (\nabla^*_{E_a} E_b, E_k). \quad (5.4)$$

This quantity shows how curved $PD(m; A, B, Q)$ is in $PD(n)$.

Theorem 5.3. The submanifold $PD(n; A, B, Q)$ is an autoparallel submanifold in $PD(n)$ with respect to $\nabla$, namely, its Euler–Schouten (imbedding) curvature is identically vanishes. Hence, $PD(n; A, B, Q)$ is totally geodesic submanifold with respect to $\nabla$, which means that $PD(n; A, B, Q)$ consists of all the $\nabla$-geodesics whose tangent vectors belong to the tangent space $TP PD(n; A, B, Q)$.

Proof. Calculating (5.4), Euler–Schouten curvature is

$$H_{abk} = J_a^i J_b^j J_k^l \Gamma_{ijk} + \left( \theta_a J_b^i \right) J_k^l g_{lk}. \quad (5.5)$$

From the facts $\Gamma_{ijk} = 0$ and $\left( J_b^i \right)$ is constant, $H_{abk}$ is found to be zero as Theorem 5.1. Since autoparallel submanifold is always totally geodesic [10], the statement follows.

Let $\{E_k\}, k = N + 1, \ldots, \hat{N}$ be the basis of orthogonally complement subspace of $\text{Skew}(n; B)$ in $\text{Skew}(n)$. On a canonically imbedded submanifold $PD(n; A, B, Q) \times \text{Skew}(n; B) \hookrightarrow PD(n) \times \text{Skew}(n)$, which has a subvector bundle structure, we can define curvature tensor $\tilde{H}_{abk}$ and $\tilde{H}^*_{abk}$ in the same manner to Euler–Schouten curvature tensor,

$$\tilde{H}_{abk} = f_P (\nabla_{E_a} \hat{E}_b, \hat{E}_k), \quad \tilde{H}^*_{abk} = f_P (\nabla^*_{E_a} \hat{E}_b, \hat{E}_k).$$

It is also easy to observe only $\tilde{H}_{abk}$ vanishes and the subvector bundle $PD(n; A, B, Q) \times \text{Skew}(n; B)$ consists of $\nabla$-geodesics. However, when it is imbedded into $PD(n) \times \text{Skew}(n, B)$ as the submanifold $\bigcup_{P \in PD(n; A, B, Q)} \left( S_0(P) + \text{Skew}_P(n, B) \right)$ by $\phi_Q^{-1} \circ \chi \circ \psi_Q$, which just embodies the structures of $S_f(A, B)$ in $S(n)$, this manifold (not subvector bundle) is generally curved even in $\nabla$-flat sense because of the origin-shifted term $S_0(P)$.
6. CONCLUSIONS

In this paper, we have dually introduced affine and fibre connections on $PD(n) \times Skew(n)$, which is diffeomorphic to $S(n)$. Then, using these connections, geometric structures of stable state feedback systems have been discussed. Connections $\nabla$ and $\tilde{\nabla}$ are proved to characterize them well. Analysis by divergences and applications of obtained results will be found in another place.

APPENDIX: THE PROOF OF THEOREM 3.2

To prove the theorem we need some notions. We illustrate them applying the abstract theory of Riemannian symmetric space \cite{11,12} to our manifold $(PD(n), g)$.

Consider the following mappings $i$ and $T$ on $PD(n)$:

$$i : P \mapsto P^{-1}, \quad T : P \mapsto TPT^T, \quad T \in GL(n; \mathbb{R}).$$

By differentiating $P \mapsto P^{-1}$, we get $i_*$, the differential of $i$ by

$$i_* : T_P PD(n) \ni X \mapsto i_*(X) = -P^{-1}XP^{-1} \in T_{i(p)} PD(n). \quad (A.1)$$

The differential of $T$ denoted by $T_T$ is

$$T_T : T_P PD(n) \ni X \mapsto T_T(X) = TXT^T \in T_{T_T(p)} PD(n). \quad (A.2)$$

Using the Riemannian metric $g$ in Theorem 1, the inner product $(\cdot, \cdot)_P$ of $T_P PD(n)$ is

$$(X, Y)_P = \text{tr} \left( P^{-1}X P^{-1}Y \right), \quad X, Y \in T_P PD(n). \quad (A.3)$$

Since (A.1) and (A.2) shows that the differential $i_*$ and $T_T$ satisfy

$$(X, Y)_P = (i_*(X), i_*(Y))_{i(p)}, \quad (X, Y)_P = (T_T(X), T_T(Y))_{T_T(p)},$$

$i$ and $T_T$ are called isometries of Riemannian manifold $(PD(n), g)$.

Define the mappings $s_P$ for each $P \in PD(n)$ by

$$s_P := T_{P^{-1/2}} \circ i \circ T_{P^{-1/2}}.$$

It is easily examined that i) $s_P$ is also an isometry, ii) $s_P^2$ is the identity, however so is not $s_P$ itself, iii) $P$ is an isolated fixed point of $s_P$. Such Riemannian manifold $(PD(n), g)$ equipped with the mapping $s_P$ for each $P \in PD(n)$ is called Riemannian (globally) symmetric.

The manifold $PD(n)$ can be identified with a quotient manifold $GL(n; \mathbb{R})/O(n)$, where $GL(n; \mathbb{R})$ is known to be $Skew(n)$. Denote the Lie algebra of $GL(n; \mathbb{R})$ by $gl(n)$. Lie algebra of $O(n)$ is known to be $Skew(n)$. Since $gl(n)$ is decomposed as $gl(n) = Skew(n) \oplus Sym(n)$, $Sym(n)$ is isomorphic to $T_1 PD(n)$. We denote this isomorphism by $dx$:

$$dx : \tilde{X} \in Sym(n) \mapsto X = 2\tilde{X} \in T_1 PD(n).$$
Lemma A.1. [11, p. 173], [12, p. 71] Let $\gamma_X(t)$ be the geodesic satisfying

$$
\gamma_X(0) = I \in PD(n), \quad \gamma_X(0) = X \in T_I PD(n).
$$

Then, $\gamma_X(t)$ is given by

$$
\gamma_X(t) = \tau_{\exp_X(I)} = \exp X t,
$$

where $X = (d\pi)^{-1} X = \frac{1}{2} X$ and $\exp$ is the exponential mapping of matrices. \hfill \Box

Since Riemannian symmetric space is complete [2,3], the exponential mapping $\exp_I$ of $(PD(n), g)$:

$$
\exp_I: X \in T_I PD(n) \mapsto \gamma_X(1) = \exp X \in PD(n),
$$

can be defined on the entire $T_I PD(n)$. Furthermore, Lemma A.1 means that $\exp_I$ is diffeomorphism between $T_I PD(n)$ and $PD(n)$ because $\exp$ is.

Proof of Theorem 3.2. We shall consider the distance between $P_1$ and $P_2 \in PD(n)$. Using the isometry $\tau_{P_1^{-1/2}}$, $P_1$ and $P_2$ are transformed as

$$
\tau_{P_1^{-1/2}}(P_1) = I, \quad \tau_{P_1^{-1/2}}(P_2) = P_1^{-\frac{1}{2}} P_2 P_1^{-\frac{1}{2}} = P_T.
$$

Consequently

$$
dist(P_1, P_2) = dist(I, P_T)
$$

because of the invariant Riemannian metric $g$. On general Riemannian manifolds $(M, g)$ the distance between $p$ and $\exp_p X$ is given by $\sqrt{g(p)(X, X)}$ [12]. Since, in our case, $\exp_I$ is given from (A.4) and (A.5) by

$$
\exp_I X = \exp X,
$$

the tangent vector $X$ satisfying $\exp_p X = P_T$ is $\log P_T$. Therefore

$$
dist(I, P_T) = (\log P_T, \log P_T)_I^{1/2} = \{\tr(\log P_T^2)\}^{1/2}.
$$

This proves the theorem. \hfill \Box

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